INFLUENCE OF ARCHITECTURAL FEATURES AND STYLES ON VARIOUS ACOUSTICAL MEASURES IN CHURCHES

By

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This work reports on acoustical field measurements made in a major survey of 41 Catholic churches in Portugal that were built in the last 14 centuries. A series of monaural and binaural acoustical measurements was taken at multiple source/receiver positions in each church using the impulse response with noise burst method. The acoustical measures were Reverberation Time (RT), Early Decay Time (EDT), Clarity (C80), Definition (D), Center Time (TS), Loudness (L), Bass Ratios based on the Reverberation Time and Loudness (BR_RT and BR_L), Rapid Speech Transmission Index (RASTI), and the binaural Coherence (COH). The scope of this research is to investigate how the acoustical performance of Catholic churches relates to their architectural features and to determine simple formulas to predict acoustical measures by the use of elementary architectural parameters.

Prediction equations were defined among the acoustical measures to estimate values at individual locations within each room as well as the mean values in each church. Best fits

with $R^2 \approx 0.9$ were not uncommon among many of the measures. Within and inter church differences in the data for the acoustical measures were also analyzed. The variations of RT and EDT were identified as much smaller than the variations of the other measures. The churches tested were grouped in eight architectural styles, and the effect of their evolution through time on these acoustical measures was investigated. Statistically significant differences were found regarding some architectural styles that can be traced to historical changes in Church history, especially to the Reformation period. Prediction equations were defined to estimate mean acoustical measures by the use of fifteen simple architectural parameters. The use of the Sabine and Eyring reverberation time equations was tested. The effect of coupled spaces was analyzed, and a new algorithm for the application of the Sabine equation was developed, achieving an average of 16% in the differences between the predicted and real RTs. Using binaural measurements and subjective information collected in these churches, BACH (Binaural Acoustical CoHerence), a new binaural measure, is presented. A linear correlation coefficient near 0.7 was found between BACH and the subjective quality ratings, supporting the hypothesis that it can be useful in predicting the quality of music in churches.

In conclusion, this study revealed important acoustical and architectural parameters and their relations, providing the basic information to predict several acoustical measures in churches at early stages of design or without the need of measurements in the real buildings.

CHAPTER 1
INTRODUCTION

1.1 Historical Analysis

Acoustics in religious buildings or places of worship as a scientific field does not have an exact date or place of birth. The acoustics of churches began when the first person made a sound in the first church. One of the first persons to write about his concerns and findings of acoustics in places of worship was the British architect Sir Christopher Wren (1632-1723). He wrote, regarding a program for 50 new churches in London, that the average parish church preacher could not expect to be intelligible farther than about 50 ft (15 m) to his front, 30 ft (9 m) to either side and 20 ft (6 m) to his back (Allen 1981). This distance of 50 ft was later supported, in 1984, when Lewers and Anderson said, "For the articulation loss to be less than 30%, according to the Peutz formula, a listener should be closer than 17 m to the pulpit" (Lewers and Anderson 1984, 296). Churches also became part of the history of acoustics indirectly when Rev. William Derham in 1708 arranged for guns to be fired from various church towers to study the velocity of sound (Lord and Templeton 1986).

For the dominant Western culture, religious buildings and places of worship usually mean churches. This is the ground for this study. "Nearly all existing forms [of churches] have evolved from the oblong, the circle, or the Greek or Latin cross" (Knudsen and Harris 1978, 331). The design of churches was affected by goals other than the acoustic one, such as the different functions of the church, its traditions, rituals and the search for architectural beauty. Nevertheless, since the late 19th century, some people have been concerned about this subject, and some elementary research studies have been undertaken. Many early studies

(1875-1928) gave some simple guidelines about acoustics in churches for specific religions, including Methodist, Episcopal (Patterson 1875) and Evangelical (Brabham 1928). However, it was not until the mid 1900s that more scientific studies were conducted.

Beginning in the early 1950s researchers Parkin and Taylor, and Raes and Sacerdote began measuring reverberation times in St. Paul's Cathedral and Roman basilicas, respectively. Many other authors have continued to measure reverberation times in places of worship, not because it is the best parameter for qualifying or grading the acoustical behavior of churches, but mainly because it is easy to measure (McCandless and Lane 1963; Shankland and Shankland 1971; Fitzroy 1973; Tzekakis 1975/79/81; Angelini et al. 1975; Fearn 1975; Popescu 1980; Lewers and Anderson 1984; Lopez and Gonzalez 1987; Marshal et al. 1987, Abdelazeez et al. 1991; Lubman and Wetherill 1985).

Several other subjective and objective acoustical parameters have been proposed by researchers since 1950, however, their application has been almost exclusively in the acoustical analysis of concert halls and auditoria (Beranek 1992). There has been very little acoustical research done specifically in churches. The few studies that exist concern the measurement of reverberation time, as described above.

1.2 Research Justification

A general goal of architectural acoustics is to design an environment with good or suitable acoustical qualities for the function (or functions) that are expected in that particular space. However, one of the factors that makes acoustics complex is that there is not a linear relationship between the physical phenomena, the inputs of the auditory system and the output interpretation made by the nervous system and the brain. Therefore, the use of experimental methods in loco has become typical.

Many authors have studied what is meant by good acoustics and how to measure it in concert halls and auditoria. But the same has not happened in churches. There is a need to consider churches as a group of buildings with special demands and characteristics regarding acoustics. "In the act of worship sound has greater impact than any other factor" (Berry and Kinzey 1954, 164). "The conventional approach to the design of the acoustic character of places of worship has been to recognize that both music and speech with their divergent acoustical needs must take place in the room because liturgy involves both" (Sovik 1973, 90). As Mills states "conditions which are most suitable for preaching are not necessarily good for music; the long reverberation in a lofty Gothic church is unsatisfactory for preaching purposes but is excellent for choral music" (Mills 1956, 61).

The interaction and coexistence of music and speech in churches and the different location and type of sound sources involved give acoustics in churches a particular position in the field of architectural acoustics and justifies this research.

1.2.1 Music and Speech in Churches

1.2.1.1 Historical evolution

Today Roman Catholic churches follow the edicts of the Second Vatican Council, but in the previous 20 centuries, different rules existed. In 1965, the Second Vatican Council introduced very important alterations in the liturgy and worship services that can have strong implications on the acoustical environment in which they are performed. That council decided that sermons should be presented to congregations in the vernacular and music that people can sing should occur in the service. These relevant changes in the speech and music of the worship services imply a new need for suitable acoustical conditions in churches.

This was not the first time in the long history of the Catholic Church that the speech and music of the liturgy underwent noteworthy transformations. One cannot even say if it was

the most important one. Until the 4th century the official language of the church was Greek. From the 4th century until the Second Vatican Council, Latin was the official language of the Church. The Second Vatican Council required a radical innovation in the liturgy of the Church. The vernacular was to be used as the official language. This has only been practiced since 1965. Throughout most of the history of the Church there was not an emphasis on understanding what was said. Therefore, suitable acoustical conditions were not needed for that task.

There were even more changes in the music included in worship services over time: from an important role in the worship until its almost total disappearance. Music was very important at the birth of Christianity. St. Paul wrote, "Speak to one another in psalms and hymns and spiritual songs, sing and make melody to the Lord with all your heart" (Ephesians 5:19). It followed the tradition of life and worship in Israel where music was central: "Let us sing to the Lord; let us make a joyful noise to the rock of our salvation . . . sing to the Lord a new song" (Psalms 95:1, 96:1). Musical instruments were allowed. The Bible mentions the use of trumpets, cymbals and other instruments.

Then, in the 4th century, the nature of music in the church was changed by a ban against the liturgical use of instruments in services. St. Jerome (340-420), a Doctor of the Church, condemned all musical instruments (Schueller 1988). Nevertheless, vocal music was allowed. In the absence of written notation, it remained simply monophonic. Over the course of many years, the assembly's voice was muted and Catholics began to ritualize without congregational music. Experts took over the song of the faithful. The assembled church changed from groups of performers to a multitude of listeners.

Another change in the church's repertoire appeared with the Gregorian chant in the 6th-7th centuries due to the rise of large monastic communities. This monophonic music with

a single melodic line was used to accompany the text of the mass and the canonical hours. The first organ was installed in a church in AD 757 in France. A few centuries later, the song of the church was transformed by the development of polyphonic music. It was the time for the motet and mass to appear in church music. Polyphonic music has more melodic lines than does monophonic music. Different voices are heard as separate entities. This gradual change in church music was due perhaps as an infiltration of folk music into the ecclesiastical arena. Erasmus wrote, "Amorous and lascivious melodies are heard such as elsewhere accompany only the dances of courtesans and clowns" (Kamien 1988, 116). Many complained that polyphony made it difficult to understand the sacred texts.

The Protestant Reformation in the early 1500s deeply shook the Catholic Church. The Church responded with a general change of its practices in what is known as the Counter-Reformation (or Catholic Reformation). In the 1530s, the Jesuits instituted year-round preaching instead of preaching only at Lent. The Council of Trent (1545-1563) understood the importance of changing worship practices to win back and to keep restless congregations. Preaching was allowed and church music was composed to inspire religious contemplation and not to give empty pleasure to the ear. These Reformations caused the return of vernacular songs sung by the people before and after mass but not during the liturgy. Pews and balconies were introduced into church buildings and the reverberation time of new churches was decreased to provide more clarity (Cremer and Müller 1978). Professionals took over the performance of church music. New musical forms such as operas and oratorios appeared. New styles evolved, flourished and succeeded through time including the Baroque, the Classic, and the Romantic.

It is important to know and understand the nature of the liturgy of the Church throughout its history and the corresponding qualities of the acoustical environment of

churches that would enhance the worship services as it changed over time. During these changes perhaps acoustical conditions were totally forgotten or perhaps they were overpowered by liturgical considerations. Therefore, the study of the influence of architectural styles on the values of room acoustic measures appears as a necessity to test these hypotheses.

1.2.1.2 Twentieth-century requirements

Today there are a large number of churches, built in the last 16 centuries and erected under different times and circumstances, that must again meet new requirements. These buildings will also face new and unknown requirements in the future. A knowledge and understanding of acoustics in churches is then essential in advancing the theoretical design of these buildings. There is a general consensus as to what the acoustical qualities of a church should be. With the new rules given by the Second Vatican Council, several acoustical characteristics of many existing churches are now inadequate. A church must have acoustical properties to support both intelligible speech and provide adequate reverberance for music. Here lies the problem because these two entities, speech and church music, have almost polar necessities for reverberation and other acoustical properties. A short reverberation time, which is preferred for the intelligibility of speech, is not suitable for church music, where a longer reverberation time is desired and vice-versa. As Kuttruff says, "When listening to speech, we are interested in perceiving each element of the sound signal. . . . When listening to music it would be rather disturbing to hear every detail including the bowing noise of the string instruments or the airflow noise of flutes. . . . These and similar imperfections are hidden or masked by reverberation" (Kuttruff 1991, 195).

In order to fully understand the sermons and other lectures, the reverberation time should be around 0.8-1.0 s depending on the room volume. For organ music, a desirable

reverberation time should be 2.0-2.2 s for enhancement of tone and blending. Here lies the difference between the desirable reverberation times for speech and music.

The Second Vatican Council demanded that the assembly must sing. This is a habit that was lost, buried under centuries of muted assemblies. With Vatican II, everyone was to become vocally and outwardly enthusiastic. But old values are hard to change. Today Catholics cannot sing. As Day states, "Ttoday a large number of Roman Catholics in the United States who go to church regularly . . . rarely or barely sing any of the music" (Day 1980, 1). The congregations are now culturally incapable of singing. The acoustical qualities of the church can also help in this matter. "Reverberance can also help the congregation avoid the feeling of *singing alone* during hymns or sung responses or *speaking alone* during prayer or responsive readings" (Egan 1988, 119). To achieve this goal of congregation participation, "Let the assembly hear its own voice, not the voice of an ego behind a microphone. Restrain the amplification. That sound of a cantor's voice sailing above the sound of the congregation and organ is perverse. It intimidates. Melt down the microphones or beat them into ploughshares" (Day 1980, 169).

A suitable sense of reverberance is not the only parameter that church buildings must have. The intelligibility of speech depends usually on the intensity of the direct sound being at a greater intensity than the reverberant sound and on its adequate loudness. The relative strength of the direct sound and the reverberant sound and loudness can be studied with several physical measures such as early to late energy ratios (C80, D, TS) and relative strength (L), discussed later. However attractive and satisfactory the interior fittings and furnishing of a church may be, "It must inevitably fail in its purpose if the acoustical properties are not conducive to good hearing" (Mills 1956, 59). The same author also says "particular consideration should be given to reducing undue strain on the preacher's voice, and here the

question of reverberation is all-important. A long reverberation period causes the prolonging of each syllable for several seconds, with the result that speech at the normal speed becomes indistinct" (Mills 1956, 60).

Since 1950 some speech intelligibility studies conducted in places of worship have been published and some authors have studied the maximum distance at which a priest can be heard without amplification (15-30 m) (Parkin and Taylor 1952a,b; Popescu 1980; Lewers and Anderson 1984; Templeton and Saunders 1987; Hammad 1990). A good acoustical environment also depends on the absence of acoustical defects, such as echoes, long-delayed reflections, sound concentrations and dead spots, and on an adequate diffusion of sound in order to have a uniform and homogeneous sound field.

The buildings of the past that have been used for Catholic places of worship do not fulfill the acoustical requirements of the current style of worship and the liturgy as revised by the Second Vatican Council. Traditional Catholic churches in southern Europe have a high ceiling, a large volume and reflective walls. These architectural features cause a long reverberation time. Many smaller chapels within the main church act as coupled spaces causing problems if the reverberation time of the chapel is not matched with the reverberation time of the main room. The shape of the ceiling can cause echoes or strong delayed-reflections. Often, many of these architectural features combine to cause large churches and cathedrals to have many acoustical problems.

Attempts to increase speech intelligibility by the use of electroacoustic amplification of sound have been made in many churches with long reverberation times and severe acoustical problems. The use of loudspeakers can create even more problems in some instances. Amplifying the music can contribute to the isolation and passivity of the congregation, going against the wishes of the Second Vatican Council. Therefore, all the situations studied and

tested in this research were done without the use of amplification or public address (P.A.) systems.

Many of the existing studies and analyses of the acoustics of churches have to do with the addition of sound reinforcement systems in the rooms. Few have addressed acoustical considerations in the initial design process. There are two general ways sound amplification systems can be used to handle the different needs of speech and music. A church can be designed for speech intelligibility with a short reverberation time. The sound of the chorus and organ can be picked up by microphones and fed through electronic reverberation units and digital delays into the loudspeakers, extending the reverberation time of the musical portion of the service (Doelle 1972). A church can be designed for music with a longer reverberation time. An electronic sound-reinforcing system will give adequate speech articulation. The system that is used in these situations with the best results is the central array system that consists of a central cluster of directional horns (Klepper 1970).

It is well accepted today that the reverberation time alone cannot completely describe the acoustical characteristics and qualities of a large room. Since the 1950s many acoustical measures have been suggested that can complement the use of the reverberation time in this task. Most of these acoustical measures are calculated from the room's impulse response (representing the beating of a room by a single loud sound) measured in loco. These factors clarify the importance in determining simple formulas to predict acoustical measures by the use of elementary architectural parameters. This is the main goal of this work.

1.2.2 Source Locations in Churches

Other acoustic situations that distinguish church buildings from concert halls, helping to justify the need for a separate analysis of this building type, are in the location and type of the sound sources involved. The physical arrangement and location of musicians within a

church are generally different from their disposition in a concert hall. One of the biggest differences is that in a concert hall the musicians perform on a stage and sound is projected to an audience located in a large area directly opposite the stage. The audience is not usually involved in the performance. It is the destination and receiver of the performance. In a worship service the musicians are just one of the performers. All the audience is performing from a large area to a stage, the altar, that represents the destination of the worship--God. In a church there are moments where just a small part of the assembly is performing, such as during a solo performance or when background music is played by only musical instruments such as the organ or when the priest is speaking.

Other contrasts between churches and concert halls include the number of musical instruments used. In concert halls there is usually a much larger number of instruments than in a church service (excluding chamber music and solo performances). In a church it is typical to have just the organ or one piano accompanied by a small group of voices (the choir) or a leading voice. When only the musical instruments are considered, the width of the sound source is wider in concert halls than in churches.

The instruments are located in different positions in churches and concert halls. In a concert hall they are usually in a central position occupying a large area and facing the audience that is on a raised floor. In a church there is usually a choir and an organ or piano that are not the central part of the performance and therefore do not occupy a central position in the room. The central position or focal point in a church is reserved for the altar. In a church the organ and the choir are often located in lateral positions or in a rear balcony. This has implications on the direction of the arrival of the direct sound to the congregation. In a concert hall the direct sound arrives from the focal point of the performance, the front. In a church it usually arrives from a secondary point in the church, the rear or one of the sides.

The senses of envelopment and intimacy can be affected by the perceived direction of the arrival of direct sound. In a concert hall environment this difference in the direction of arrival of sound would have strong implications on the subjective quality of the music. In a reverberant church, that effect is attenuated. This difference is increased when the audience sings together with the organ. The sounds come from many locations other than the front center of the church.

When other musical instruments instead of an organ are used in a church, additional problems can be present. For liturgical reasons, "It is important to avoid physical settings reminiscent of a stage or other entertainment venue" (Milwaukee 1992, 50). The body of the church is typically too long and the ceiling too high to maintain a suitable sound quality. The sound quality reduces rapidly with distance towards the rear of the congregation. Woodwind instruments suffer and the strings lose strength and vibrato. Only brass and percussion instruments withstand the conditions (Lord and Templeton 1986). The presence of sound-absorbing materials in the musicians' area can have a very important influence on loudness throughout the church and on the pattern of the early sound energy distribution. Therefore the use of carpet, pew cushions, curtains or other sound-absorbing material should be avoided in that area of the church. Choir areas should be higher than the congregation and close to reflecting surfaces such as walls, and never placed in deep recesses to allow projection of their sounds into the main volume of the church. Considering all the acoustical problems that a church can have, the locations of the choir, organ and organ console must be carefully chosen because once installed, the organ and choir risers cannot be easily moved.

The findings that have been published in this area present some basic guidelines and checklists regarding specific points that can help the designers of worship spaces (Doelle 1972; Egan 1988; Moore 1988). These simple checklists include information on items such as the

position of the pulpit and organ, the shape of the ceiling, the treatment of coupled spaces, the treatment of floor and pews, the achievement of strong lateral sound and limits on acceptable levels of background noise. In many cases these rules of thumb and standard practices are summaries of traditional design practices that are usually not supported by scientific research.

It is essential to shape an appropriate auditory environment for worship. Even the hierarchy of the Catholic Church explicitly expects this. "An acoustical consultant who recognizes the unique demands of liturgical space should be employed in the design and construction process" of churches (NCCB 1979). To comply with this goal there must be enough knowledge, supported by large data bases and reliable guidelines, to sustain the work of the acoustical designers of churches. Therefore, a need exists to better understand and characterize the different aspects of acoustics in churches. The general goal of this study is to develop this increased understanding of the acoustics of churches in one area: the relationship of basic architectural features and styles of churches with representative acoustical measures.

1.2.3 Summary Justification for the Research

Churches represent a particular type of building with specific acoustical requirements and important historical variations in requirements and functions. The acoustics of churches have not been studied in depth to date. There is a need to find what constitutes the acoustical environment of a church and to gain a better understanding of the acoustical conditions in these rooms. The analysis of the acoustics of churches can be divided into two different areas: the physical phenomena and the psychophysiological response. This research investigates the relations among the physical phenomena of sound buildup and distribution in churches as characterized by six acoustical measures and the architectural features of the churches to calculate prediction equations for the acoustical measures.

1.3 Research Assumption and Purpose

The basic assumption, supported by previous work in this area of research (sections 1.1 and 1.2), is that the acoustical response of the room varies within and among churches. It is presumed that there are differences in the way the rooms respond to acoustical impulses emitted from a position within a church as well as differences in the mean values of acoustical measures from church to church. According to these presumptions, the main goal of the dissertation is to identify the main acoustical characteristics and variations that are present in churches. The purpose is to develop an understanding of the ways in which the architectural features of the rooms relate or interact with the acoustical behavior of the room and to identify the relationships between church shape and sound. These are characterized, respectively, by the architectural features and by the sound buildup and distribution measures within the churches.

The main scope of this research is to investigate one critical area of acoustics in churches: the relationships of basic architectural styles, dimensions and materials of churches to detailed acoustical measurements made at multiple locations within each room. As explained above, many factors interact simultaneously to build a particular acoustical environment in churches. Therefore, this study needs to analyze several aspects of the same problem and to scrutinize their independent contributions to the acoustical performance of churches. To achieve this specific purpose, analyses are performed in various concurrent areas of acoustics in churches. The principal aim is to calculate relationships formulas and prediction equations for representative acoustical measures based on characteristic architectural parameters. Therefore, relationships among acoustical measures and between acoustical measures and architectural parameters are investigated and then organized in logical sequences of groups of similar statistical analyses.

This investigation follows the latest studies and developments regarding acoustics in concert halls and adapts the processes and experimental algorithms to the specific characteristics of the acoustics of churches. Therefore, the research questions are based on previously published works in the comparable field of acoustics in concert halls.

The knowledge and understanding of how acoustical measures vary and their inter-relationships in concert halls were the basis for the first group of research questions (Jordan 1981; Bradley 1989; Gade 1989; Siebein et al. 1992; Tachibana and Yamasaki 1993). Adaptations to the processes and results developed by the research in concert halls were made regarding the particularities of the church environment. Therefore, the research questions are as follows. How are the acoustical characteristics of churches described by impulse response measurements? What are the typical expected values of the various physical measures in particular types of churches? How can they be predicted from other measures? What are the relationships among these measures? Is there any significant variability in acoustical characteristics regarding the date or style of construction of the churches? Is there any variability in the acoustical characteristics among different types of churches? That is, how much within or inter-church variation is to be expected in specific situations? It is hypothesized that differences can be found in the values of acoustical measures within and among churches. It is also expected that prediction equations can be drawn to relate acoustical measures among themselves. This study is expected to reveal differences in the acoustical measures between sound source positions. It is also hypothesized that changes in architectural styles affected the acoustical characteristics of churches.

The knowledge and understanding of how the architectural features of a building can interact with its acoustical characteristics in concert halls were the basis for the second group of research questions (Gade 1990/91; Chiang 1994). Therefore, the second group of research

questions are as follows. What are the architectural features of churches that are related to the values of acoustical measures? That is, how do values of the acoustical measures relate to the geometry and materials of churches? How can the room architectural parameters be used to predict physical acoustical measures? It is hypothesized that several architectural parameters have strong relations with individual acoustical measures. It is expected that prediction equations can be calculated to easily but largely explain the variance found in the values of the acoustical measures.

Several authors (Shankland and Shankland 1971; Tzekakis 1981; Trochidis 1982) found some difficulties in using traditional equations to estimate reverberation times in churches due to the existence of recesses that sometimes act as coupled spaces. How can the traditional reverberation time equations (Sabine or Eyring) be easily applied to this type of space? It is hypothesized that the classical equations to calculate reverberation time can be used in churches with reasonable results. It is expected that the coupled spaces effect is responsible for the major discrepancies in the use of these formulas.

Speech intelligibility in churches has been studied, but there is still no large collection of data to allow a complete understanding of what architectural features and acoustical measures are related to the intelligibility of speech in Catholic churches (Parkin and Taylor 1952a,b; Anderson and Jacobsen 1985; Bradley 1986a,b; Hammad 1990). Therefore, an additional group of research questions are as follows. How suitable are churches for understanding speech? How did speech intelligibility change over time in churches? What is the overall acoustical importance of traditional pulpits? It is hypothesized that speech intelligibility in churches is generally very poor and that there are identifiable changes over time in its measurable acoustical quantity. It is expected that pulpits have a favorable acoustical influence on speech intelligibility in churches.

Music was and is an important part of church services. This study cannot be complete without a look into this area. How suitable are the churches assessed as regards to the performance of musical events? How can the quality of a church for musical performances be predicted? It is hypothesized that churches can be a suitable environment for musical performances justifying their use for this function in many countries. It is also hypothesized that a new binaural acoustical measure can be defined to predict the subjective quality of musical performances in churches. Each of these groups of research questions will be analyzed and answered in a separate chapter throughout this text.

CHAPTER 2
METHOD

2.1 The Sample

The main investigation is focused on the Roman Catholic churches of Portugal. Portugal is one of the oldest European countries and played a prominent role in some of the most significant events in world history. It presents an almost perfect location to trace the history of Catholic church buildings in the world. Portuguese churches can be considered a representative example of Catholic churches in the world (Gil 1992; DGEMN 1936/64; Azevedo 1985).

This study reports on acoustical field measurements in a major survey of 41 Roman Catholic churches in Portugal that were built between the 6th century and 1993. Table 2.1 presents an alphabetical list of the churches tested in the survey. The location of each church is shown on the map of Portugal in Figure 2.1. The churches are a sample of 14 centuries of church building in Portugal. The oldest church tested was number 26 (*S. Frutuoso de Montélios*), which was built around the 6th century. The most recent was church number 35 (*Seroa*), which was completed in 1993. A complete analysis, with drawings and a basic description of all the churches tested, was published as an internal report in the University of Florida's College of Architecture (Carvalho 1994).

The churches were selected to represent the main architectural styles found throughout Portugal and to represent the evolution of church construction in Portugal. The architectural styles of the churches are presented in Table 2.2. For more uniformity of the sample and due

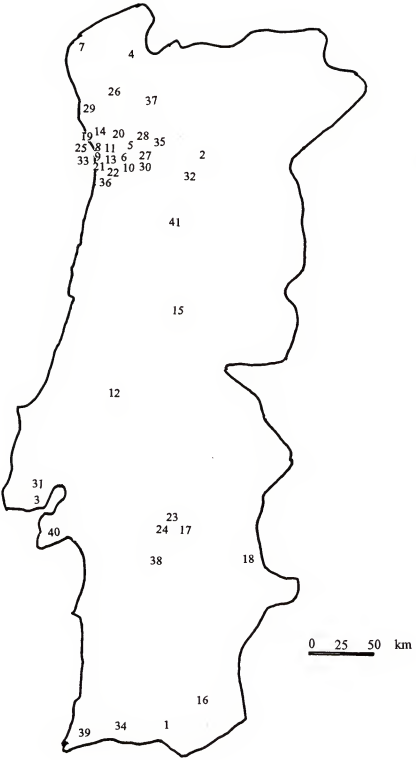


Figure 2.1 - Map of continental Portugal with the 41 churches tested.

to the sound power limits of the sound source, only churches with a maximum volume of less than 19000 m^3 were selected for the study.

TABLE 2.1 - List of 41 churches tested.

N.	CHURCH NAME	VOLUME (m^3)	N.	CHURCH NAME	VOLUME (m^3)
1	ALMANSIL	578	22	SANTA CLARA (PORTO)	2491
2	ARMAMAR	2487	23	S. B. CASTRIS (ÉVORA)	1314
3	BAS. ESTRELA (LISBOA)	18674	24	S. FRANCISCO (ÉVORA)	18631
4	BRAVÃES	946	25	S. FRANCISCO (PORTO)	12045
5	BUSTELO	6476	26	S. FRUTUOSO	320
6	CABEÇA SANTA	751	27	S. GENS (BOELHE)	299
7	CAMINHA	5899	28	S. PEDRO DE FERREIRA	2912
8	CEDOFEITA-NEW (PORTO)	8470	29	S. PEDRO DE RATES	3918
9	CEDOFEITA-OLD (PORTO)	1117	30	S. PEDRO DE RORIZ	2198
10	CETE	1515	31	S. ROQUE (LISBOA)	14207
11	CLÉRIGOS (PORTO)	5130	32	SÉ (LAMEGO)	13424
12	GOLEGÃ	5563	33	SÉ (PORTO)	15260
13	LAPA (PORTO)	11423	34	SÉ (SILVES)	10057
14	LEÇA DO BAILIO	9795	35	SEROA	4225
15	LOUROSA	1163	36	SERRA DO PILAR (GAIA)	11566
16	MÉRTOLA	1950	37	TIBÃES	8608
17	MISERICÓRDIA (ÉVORA)	3338	38	VIANA DO ALENTEJO	3358
18	MOURA	6300	39	VILA DO BISPO	1290
19	N. S. BOAVISTA (PORTO)	3740	40	V. N. AZEITÃO	1239
20	PAÇO DE SOUSA	6028	41	VOUZELA	1148
21	SANT. SACRAM. (PORTO)	6816			

TABLE 2.2 - Architectural styles of churches tested.

1 - VISIGOTHIC	(6th-11th centuries)	*5 - RENAISSANCE*	(16th-17th centuries)
2 - ROMANESQUE	(12th-13th centuries)	*6 - BAROQUE*	(17th-18th centuries)
3 - GOTHIC	(13th-15th centuries)	*7 - NEOCLASSIC*	(18th-19th centuries)
4 - MANUELINE	(15th-16th centuries)	*8 - CONTEMPORARY*	(20th century)

Acoustical measurements were taken in similar numbers of churches grouped by large periods of history: 12 Visigothic or Romanesque churches (6th-13th centuries), 16 Gothic or Manueline churches (13th-16th centuries), 13 Renaissance, Baroque or Neoclassic churches (16th-19th centuries) and 4 Contemporary churches (20th century). The main architectural features of these churches are displayed in Table 2.3.

TABLE 2.3 - Simple statistics for all churches tested.

ARCH. FEATURE	Min.	Max.	Mean	Median
VOLUME (m^3)	299	18674	5772	3918
AREA (m^2)	56	1031	450	427
MAX. HEIGHT (m)	7	39	15	13
MAX. LENGTH (m)	12	62	33	31
WIDTH NAVE (m)	4	38	13	11

2.2 Procedure

2.2.1 Acoustical Measures

Several authors have suggested the use of new acoustical measures in concert halls and auditoria (Jordan 1981; Bradley 1982/89/90; Gade 1989; Beranek 1992). More than 20 measures have been proposed to measure some aspect of room acoustics. Using the literature available, which was primarily studying concert hall acoustics, several measures were considered to be applicable to analyze the acoustics of churches. Six monaural acoustical measures were chosen to provide the greatest potential to describe the dual functions of speech and music found in churches. The measurements chosen included Definition (D) for speech; C80 (Clarity) and Center Time (TS) for music; and Reverberation Time (RT) and Loudness (L) for their hypothesized role in characterizing the overall acoustical impression in a room. Reverberation time was also included because it remains the single most used measure to characterize a large room (Barron 1994). Loudness was included due to its strong relation with the senses of loudness and intimacy (Cremer and Müller 1978; Barron 1988/94). The sense of acoustic intimacy, to feel involved or detached from the sound performed, is, in a church, an important subjective quality and perhaps plays a role in the creation of an environment of mystique or dignity in the place. The six acoustical measures are defined in detail below.

Reverberation Time (RT) is the time it takes for sound to decay 60 dB. It was proposed by W. C. Sabine in 1900 (Sabine 1992). It is usually measured from a decay of 30 dB (from -5 to -35 dB or also RT30) and then multiplied by a factor of 2 as expressed in the following formula: $RT = 2\ [\ SD^{-1}(35) - SD^{-1}(5)\ ]$

where SD (t) = Sound decay as a function of time and SD^{-1} (t) = Inverse function of SD(t).

In this study RT was calculated from reverse integration of the logarithmic decay curve obtained from an impulse response (Schroeder 1965). RT is suggested to be a measure of the subjective sense of reverberance (Beranek 1962; Barron 1988; Chiang 1991; Müller 1992), however, to a lesser degree than EDT.

Early Decay Time (EDT) is the time it takes for sound to decay 60 dB. It was proposed by Jordan based on research made by Atal et al. in 1965 (Jordan 1970). It is an adaptation of the reverberation time now measured from a decay of 10 dB (from 0 to -10 dB or also EDT10) and then multiplied by a factor of 6 as expressed in the following formula:

$$EDT = 6\ [\ SD^{-1}(10) - SD^{-1}(0)\ ].$$

In this study EDT was calculated as described above for RT. EDT is suggested to be a measure of the subjective sense of reverberance (Cremer and Müller 1978; Barron 1988; Chiang 1991/94), clarity (Chiang 1994) and overall acoustical impression (Cervone et al. 1991).

Early to Late Sound Index or Clarity with a time window of 80 ms (C80) is one ratio of early-to-late sound energy or early-to-reverberant sound energy ratio C*t* or EL*t* (typically C80, but C30, C50 or C100 are also used). It is the ratio in dB between the energy received in the first *t* seconds of the received signal and the energy received afterwards. It was proposed by Reichardt et al. in 1975 where the limit of 80 ms was proposed as the limit of perceptibility for music. It is calculated by using 10 log of the ratio of the integrated squared

pressure, arriving before the time *t*, to that arriving after time *t*. In concert halls C80 usually lies between -2 and 2 dB. C80 is suggested to be a measure of the sense of clarity (Chiang 1991/94):

$$C80 = 10\log\frac{\int_0^{80} p^2(t)dt}{\int_{80}^{\infty} p^2(t)dt}$$

where $p(t)$ is the time function of the impulse response of the enclosure measured using a microphone at a particular location in the room.

Early to Total Energy Ratio, Early Energy Fraction, Definition or *Deutlichkeit* with a time window of 50 ms (D) is the ratio between the energy received in the first 50 ms and the total energy received. It lies between 0 and 1. D was proposed by Thiele in 1953. The duration of 50 ms was called the limit of perceptibility regarding speech. It is hypothesized to be a measure of how clear a sound appears to a listener--the higher the D, the clearer the sound:

$$D = \frac{\int_0^{50} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}.$$

Center Time (TS, where the S stands for the German *Schwerpunkt*, center of gravity) is the point in time where the energy received before this point is equal to the energy received after this point. It was proposed by Cremer and Müller in 1978. It is also hypothesized to be a measure of how clear a sound appears to a listener--the lower the TS, the clearer the sound. It usually lies between 140 and 180 ms in concert halls (in the frequency range 250-2000 Hz).

$$TS = 10\log\frac{\int_0^\infty t.p^2(t)dt}{\int_0^\infty p^2(t)dt}.$$

Loudness, Total Sound Level, Overall Level or Strength of arriving energy (L) is the ratio, in dB, of the total energy received at a particular position in the enclosure and the energy received due to the direct sound alone (measured at a distance of 10 m from the source in an anechoic environment). It was first used by Gade and Rindel in 1984 following ideas introduced in earlier studies (Yamagushi 1972; Lehmann 1976; Cremer and Müller 1978). Loudness is a measure of the aptitude of a room to intensify sound in a particular position when compared with an anechoic environment. It is also used to verify the room's sound field uniformity and to analyze if the transmitted energy to the room is deficient at some frequencies. Loudness usually lies between 3 and 9 dB in concert halls. This measure is also denoted as G in the literature. It is suggested to be a measure of the sense of loudness (Schroeder et al. 1974; Cremer and Müller 1978; Barron 1988; Chiang 1994) and intimacy (Barron 1988):

$$L = 10\log\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt}$$

where $p_{10}(t)$ is the time function of the impulse response in free field conditions at a distance of 10 m.

Much in the available literature regarding concert halls and auditoria suggest that some of these acoustical measures are highly correlated (Wilkens 1975; Lehmann 1976; Gade 1990; Siebein et al. 1992). The author prefers to use those measures separately due to the different conditions that are hypothesized to be present in churches regarding diffusion and the shape of

the decay curve (not perfectly exponential) that will permit more differences in those values within the room and more variability among them and also to test the relationships among these acoustical measures.

Graphical analyses were also taken using Reflectograms and Decay Curves regarding their shape, differences and similarities among frequency bands and receiver and source positions. A reflectogram is the plot of amplitude measured in dB on the vertical axis and time measured in *ms* in the horizontal axis of the room's response to an impulse sound source over a period of time. The impulse response illustrates the distribution over time and the amplitude of the direct and reflected sounds arriving at a specific location of the room. A decay curve is the reverse integration of sound pressure level plotted versus time, and it shows the sound decay in a room.

The method used to calculate the acoustical measures is based on the integrated impulse-response method described by Schroeder in 1965. A limited-bandwidth noise-burst is generated and transmitted into the church by a loudspeaker via an amplifier. The room's response to the noise-burst (called the impulse response) is then sampled from the RMS detector output of the sound level meter (Brüel & Kjær 1990).

For the calculations of L (Loudness) a reference file was previously determined. This reference file was set up for a given amplifier, setting, loudspeaker and height combination by measuring the output of the amplifier-loudspeaker combination in a reverberant room and calculating the values the noise doses would have if measured under the reference conditions (i.e., in the free field at a distance of 10 m). This procedure was performed in the 120 m^3 reverberant chamber of the L.N.E.C. (National Laboratory of Civil Engineering) in Lisbon, Portugal.

Rather than a pistol, a loudspeaker emitting noise (short noise pulse bursts) in 3/2 octave frequency bands (to ensure that the received noise-burst is of 1/1 octave bandwidth) was used as sound source. For a specific power amplifier this system allows more energy to be transmitted into the room than with a pistol. This advantage is especially important when background noise is present. The pistol is a very powerful and practical sound source. However, its shots usually lack energy in the lower frequency bands and reproducibility (Brüel & Kjær 1988). Moreover, a pistol shot may be of too short duration to allow the noise to attain a steady level in the room (Brüel & Kjær 1980).

The receiving section consisted of one 1/2" diameter microphone (which changed position throughout the room) and a sound level meter with a 1/1 octave filter set. A filter centered on the same frequency as the filter in the transmitting section reduces the influence of background noise.

The procedure was commanded by specific control software (*Room Acoustics*) using a notebook computer in loco. The loudspeaker was placed at two sound source locations in each church: one in front of the altar to standardize the measurements and to be able to compare results among churches and another in the center of the main floor to simulate the sound of the congregation. The sound source was positioned at 0.8 m above the floor and at a 45° angle with the horizontal plane. That angle was chosen to transmit more energy into the room volume, to try to better excite the reverberant field of the church. This loudspeaker position also gave more omnidirectionality to the sound source by locating the sides of the loudspeaker with less directivity such as in the back, facing the floor. A diffuser, a conical piece snap-locked onto the front of the cabinet, was used to render the measured results less dependent on the position and angle of inclination of the cabinet and to lower the directivity coefficient values. Appendix A presents the directional characteristics of the sound source used.

Each measurement was calculated from an ensemble of three and four pulse responses in each position. This number of samples was chosen considering the high quality of the reproducibility of the sound source used, the number of samples used in the recent past of room acoustics as seen in the available literature, and the experience acquired by previous measurements made by the Acoustic Laboratory of the University of Florida College of Architecture. Five receiver positions were, on average, used, depending on the width of the church (see Figure 2.2). The microphone at each location was placed at 1.30 m above the floor. In total, nearly 8000 values were determined (all combinations of frequency bands and source/receiver locations).

2.2.1.1 Bass ratios

Two bass ratios were calculated: BR_RT and BR_L proposed by Beranek (Beranek 1962) and Gade (Gade 1989). They are usually used to evaluate balance by comparing the loudness and reverberation times for the low frequencies to the loudness and reverberation times for the high frequencies. They are usually used to evaluate the subjective sense of timbre, tonal balance or warmth. They are defined by the following equations:

BR_RT - Bass Ratio based on Reverberation Time

$$BR\_RT = [RT(125) + RT(250)] / [RT(500) + RT(1k)]$$

BR_L - Bass Ratio based on Loudness

$$BR\_L = [L(125) + L(250) - L(500) - L(1k)] / 2$$

where RT is the reverberation time for the specified octave bands and L is the overall level for the specified octave bands.

2.2.1.2 RASTI

Speech intelligibility was quantified by the calculation of the Rapid Speech Transmission Index (RASTI) which may be related to the scores of people taking standard

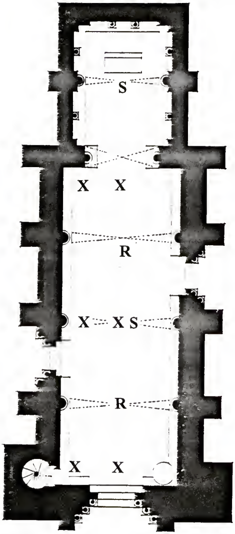


Figure 2.2 - Typical locations for receivers and sound source (R-Receiver positions only for RASTI measurements, S-Sound source positions, X-Receiver positions for determination of acoustical measurements and RASTI).

speech intelligibility tests (Brüel & Kjær 1986). This method is based on the measurement of the reduction in signal modulation between the speaker and listener positions. A transmitter generates a special test signal (pink noise in the 500 Hz and 2000 Hz octave bands) to mimic the long-term speech spectrum. An omnidirectional 1/2" diameter microphone receives the signal. The signal is transmitted to the RASTI receiver unit, which analyzes the signal and calculates the RASTI value that is immediately displayed in the display screen. The receiver and transmitter are independent units (not synchronized) because the signal is repetitive (Brüel & Kjær 1986). In each church the transmitter location was in front of the altar, 1.65 m above the floor. Several positions (from 4 to 17) were used for the receiver depending on the length of the church (on average, eight positions were in fact used). In each receiver position three or four measurements were taken and then averaged together to give the RASTI value at that location.

2.2.1.3 BACH

Binaural measurements were also taken using the dual channel real-time frequency analyzer. In the simultaneous analysis of signals it is no longer the signals themselves that are of primary interest, but rather the properties of the physical system responsible for the differences between them. The author tested the hypothesis that a new binaural acoustical measure can be useful in room acoustics studies. The idea is to use both instant spectra (Channel A and Channel B inputs) and their cross spectrum to find the coherence values.

Channels A and B are microphones placed at both ears of a test person in the middle main floor (central nave). A pink noise source was used with the loudspeaker in front of the altar (height of 0.8 m).

The coherence gives a measure of the degree of linear dependence between the two signals, as a function of frequency. It is calculated from the two autospectra and the cross

spectrum. It can also be interpreted as a squared correlation coefficient expressing the degree of linear relationship between two variables. If the coherence is *1* there will be a perfectly linear relationship between both signals at both ears. If it is *0*, there is no relationship whatsoever between ear signals (Randall 1987). The new binaural acoustical measure was called BACH, Binaural Acoustic CoHerence. In each church, three spectra were recorded in the same position (only one position was selected). The values were then averaged for further analysis to test the validity of this measure in identifying differences among churches (see Chapter 7).

2.2.1.4 Subjective analysis

Very basic qualitative information was collected in each church by interview with the local priests and/or other members of the staff. Answers were requested to simple questions such as if the church had good acoustics or good sound, if the music sounded good, if there were musical performances in the church and which type, if the performers liked the sound of the church, etc. The churches were then rated on a five point scale: Very Bad, Bad, Normal, Good or Very Good acoustics. The subjective analysis is not the main goal of this research, so this information was intended to be a pilot study for future research.

2.2.2 Occupied vs. Unoccupied

The churches were measured while unoccupied as the available state of the art does not allow easy and practical acoustical measurements to be made in an occupied room. The high noise level of the sound source and the long duration of the measurements make the presence of a quiet congregation almost impossible. Furthermore, the use of absorptive materials to simulate the presence of people is also impractical due to the huge amount needed. In addition, most of the available bibliographic data were determined for unoccupied conditions. Therefore consistency of data is useful for possible comparison purposes.

However, another perspective is possible: In the past (until a few centuries ago) there were no pews or chairs for people in the churches. For that reason, the total absorption in today's unoccupied churches with a large number of pews may not be greatly different in some frequency bands, particularly the higher bands from the acoustical conditions of the churches in the past with no pews and a smaller congregation. The difference can be seen then in another dimension, time--almost as an exercise of archaeological acoustics.

2.3 Equipment

Equipment from the Acoustical Laboratory of the University of Porto College of Engineering was used. For the acoustical measures the equipment used was sound level meter Brüel & Kjær type 2231; 1/3-1/1 octave filter set Brüel & Kjær type 1625; module Room Acoustics Brüel & Kjær type BZ7109; sound source Brüel & Kjær type 4224; microphone 1/2" diameter Brüel & Kjær; notebook computer Compaq LTE 386-25 MHz; and application software Room Acoustics Brüel & Kjær VP7155. For the RASTI measurements the equipment used was speech transmission meter Brüel & Kjær type 3361 consisting of transmitter type 4225 and receiver type 4419; and microphone 1/2" diameter Brüel & Kjær type 4129. For the other measurements the equipment used was dual channel real-time frequency analyzer Brüel & Kjær type 2144; two 1/2" diameter microphones Brüel & Kjær type 4165; two microphone preamplifiers Brüel & Kjær type 2639; and application software Brüel & Kjær type 5306.

2.4 Pilot Study

2.4.1 Method and Purpose

The research method was tested prior to its final application. Three churches in Porto, Portugal, were tested in December 1992. The main goals of the pilot study were to test the basic assumption of this research (Chapter 1), to test the equipment (hardware and software)

and to find any difficulties associated with the practical aspects of the research such as the availability of graphical data, accessibility of churches, duration of measurements, etc. On the basis of participants' comments and on the results found, the research method was further developed and basic knowledge was found regarding several aspects of the method to be used.

2.4.2 Results

A pilot study was conducted (Appendix B) to study how the number of positions at which measurements were recorded in each church affected the within church differences of room acoustics measures. The results of the pilot study showed that the number of positions in a church at which acoustical measures were taken is more important for the C80, D and TS measures than for RT and EDT. In these cases two positions are clearly insufficient and there are no significant improvements from choosing more than eight positions. The number of positions used in this study was set at five or six positions depending on the width of the church.

There are several different methods of data averaging among positions in churches. A pilot study was conducted (Appendix C) to determine if there are significant differences using two distinct methods of averaging and to use this knowledge in the later analysis of the data to be collected in the field trip. One church was selected and two averaging methods were tested. Average 1 had no different weight assigned among positions. Each data position has the same weight in the average. Average 2 had the data weighted by the number of seats surrounding each position. The differences found between the methods are much smaller than the respective standard deviation for all the acoustical measures. In the RT and EDT data there are no significant differences at all. For that reason, the conclusion is that there is no need to be very careful in choosing the location for the microphones. Fairly evenly distributed positions will be sufficient. There is also no need to average the data by the number of seats

involved. This was an important conclusion in choosing the position of each receiver location within the churches.

2.5 Field Trip

To measure the churches a field trip was taken during the Summer 1993. From May to August nearly 2,000 miles were driven around Portugal to accomplish the desired goal. During that time, 41 Portuguese Roman Catholic churches were chosen and acoustically tested. In each of the 41 churches tested, the same procedure was used. That was the filling out of a field form, making the acoustical measurements with the RASTI and other measurements including the binaural coherence and finally taking notes and interviewing for documentation and for the subjective studies.

In each church a three page field form was completed with notations regarding architectural data taken by personal observation. The subjects recorded were date and time; number and type of seats; surface materials and finishes; location of the microphones and sound source; lateral chapels; windows; drapery and number of statues; general subjective analysis; and particular observations.

CHAPTER 3
ACOUSTICAL MEASURES

3.1 Purpose

The purpose of this Chapter is to characterize the selected acoustical measures in their use in the analysis of the acoustics of churches. The goal is to analyze how the acoustical measures vary within and among churches, among architectural styles, and to find their inter relationships. To check the validity of the hypotheses presented in Chapter 1, five primary analyses of the six acoustical measures (RT, EDT, C80, D, TS and L) were performed.

The analysis of the acoustical measures, their behavior (regarding within or among room variations, sound source location, etc.) and their correlations among themselves was performed. The analysis of the within and inter church variation of the acoustical measures was conducted. The analysis of the effect of sound source position in the acoustical measures values was tested. The analysis regarding the effect of architectural styles on the acoustic measures was done. The diffuse classical theory was used to calculate estimations of some acoustical measures and these estimations were used in the prediction regression models as corrections to the models done using only architectural parameters.

3.2 Relationships among Acoustical Measures

3.2.1 Procedure

Statistical analysis was used to determine relationships among the six acoustical measures (RT, EDT, C80, D, TS and L). Two approaches were followed: 1) using ALL DATA and 2) using AVERAGED DATA. The statistical analysis with all data was performed with nearly 2030 data-points obtained considering all positions and all six frequency-bands

(125 to 4000 Hz) measured. Each data-point is the result of the average of the 3 or 4 impulses recorded in that location and for that particular octave-band. In the averaged data analysis one value was calculated as the average of all source-receiver position results and using all six octave frequency bands. Therefore, 41 data-points were calculated (one for each church). Linear and nonlinear models were used in order to determine the best regression line for the correspondence between each two acoustical measures. The models tested were the linear ($y=a+b.x$) and some non-linear: logarithmic ($y=a+b.log_n x$), quadratic ($y=a+b.x+c.x^2$), cubic ($y=a+ b.x^3$) and exponential ($y=a+b.e^{c.x}$).

3.2.2 Using all Data

Table 3.1 presents a general statistical general analysis of the results found using all data (around 2030 points). Table 3.2 presents the absolute values of the correlation coefficients (R) for the relationships among the six acoustical measures. For each case there are two R values shown ($|R_{linear}|$ [$|R_{best\ fit}|$ smooth). The R_{linear} (left) used the linear regression model and the $R_{best\ fit}$ (right) used the best-fit model obtained from all the tests (linear, logarithmic or quadratic smooth).

TABLE 3.1 - Simple statistics of acoustical measures (all source/receiver positions).

Measure	Minimum	Mean	Maximum	St. Dev.
RT (s)	0.8	3.2	9.3	1.7
EDT (s)	0.6	3.1	10.8	1.6
C80 (dB)	- 14.2	- 3.0	11.2	3.7
D	0.01	0.24	0.88	0.16
TS (ms)	33	226	670	119
L (dB)	1.0	13.3	27.9	4.2

Figure 3.1 presents each one of the previous relationships studied, in scatterplot matrixes (casement plots), with the best fit applicable. The equations for each of the best fit regression line are shown in Table 3.3.

TABLE 3.2 - Correlation coefficients ($|R_{linear}|$ [$|R_{best\ fit}|$ smooth) among acoustical measures (using all data).

Measure	RT	EDT	C80	D	TS
EDT	0.99[**0.99**lin	-	-	-	-
C80	0.68[**0.75**log	0.70[**0.78**log	-	-	-
D	0.51[**0.59**log	0.53[**0.62**log	0.92[**0.94**qua	-	-
TS	0.91[**0.91**lin	0.94[**0.94**lin	0.85[**0.93**log	0.71[**0.84**log	-
L	0.08[**0.19**qua	0.09[**0.21**qua	0.35[**0.35**lin	0.35[**0.35**qua	0.21[**0.31**qua

TABLE 3.3 - Best fit equations among acoustical measures (using all data - all 2031 points).

$EDT = 0.043 + 0.941\ RT$	$D = 0.347 + 0.048\ C80 + 0.0016\ (C80)^2$
$EDT = 0.219 + 0.013\ TS$	$D = 1.562 - 0.25\ \log_n (TS)$
$C80 = 2.876 - 5.572\ \log_n (RT)$	$D = 0.140 + 0.0011\ L + 0.00045\ (L)^2$
$C80 = 2.784 - 5.735\ \log_n (EDT)$	$TS = 17.821 + 64.203\ RT$
$C80 = 30.937 - 6.422\ \log_n (TS)$	$L = 16.683 - 1.828\ RT + 0.190\ (RT)^2$
$C80 = - 7.071 + 0.308\ L$	$L = 16.790 - 1.926\ RT + 0.201\ (EDT)^2$
$D = 0.439 - 0.190\ \log_n (RT)$	$L = 18.148 - 0.035\ TS + 0.000047\ (TS)^2$
$D = 0.439 - 0.197\ \log_n (EDT)$	

Among all respective relationships, the highest correlation was seen between RT and EDT ($|R| = 0.986$) because they are very similar physical quantities; Very high correlations ($|R| \approx 0.94$) were also found between C80 and D, EDT and TS or RT and TS; The correlations between L and the other measures are very low ($|R| < 0.36$) representing a significant poor relationship among them and making L orthogonal to the other five acoustical measures.

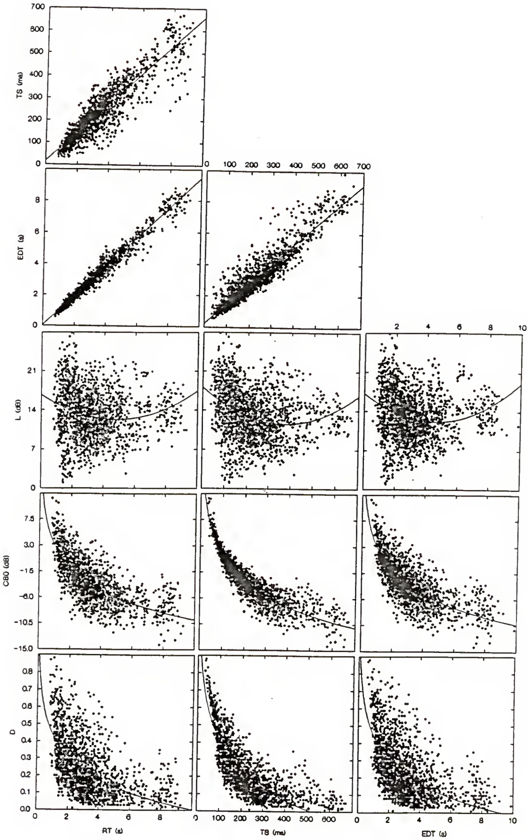


Figure 3.1 - Scatterplot matrix (casement plot) for relationships among acoustical measures with regression models using all data (2030 points).

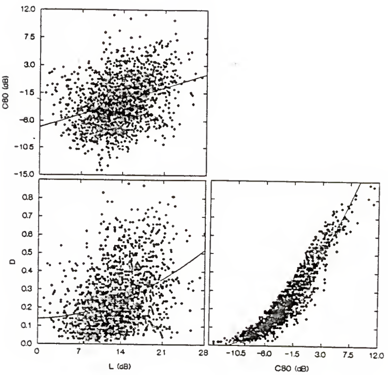


Figure 3.1-- continued.

3.2.3 Using Averaged Data for Each Church

3.2.3.1 The search for a representative single number average

A similar analysis among the six acoustical measures was done using only one average value for each acoustic measure for each church tested. Instead of performing a statistical analysis with 2030 points (all frequency bands and source/receiver positions), only 41 points are now used (1 for each church). To choose which averaging method is the most suitable for this type of study, several analyses were done. Seven options for averaging methods were tested as shown in Table 3.4.

Tables in Appendix D present the averaged values calculated for each church using those seven options for the acoustical measures. The analysis of the behavior of each of these seven options and the usefulness concerning their influence in the results of the relationships among the acoustical measures are presented in Appendix E. This is not a vital point because there is no fundamental necessity for a single-number in the analysis of the acoustical measures and their relationships among themselves. An average value of each acoustical measure for each church is required for the analysis of the architectural parameters which is the fundamental issue addressed in this research. Later a similar analysis will be done concerning those relationships between the acoustical and the architectural parameters.

TABLE 3.4 - Seven options of frequency averaging methods.

CODE	DEFINITION
41_ALL	Average of all 6 frequencies (125 to 4000 Hz octave bands)
41_W24	Average of the 4 lowest frequencies (125 to 1000 Hz octave bands)
41_4H	Average of the 4 highest frequencies (500 to 4000 Hz octave bands)
41_4M	Average of 4 middle frequencies (250 to 2000 Hz octave bands)
41_3F	Average of 3 medium frequencies (500, 1000 and 2000 Hz octave bands)
41_O24	Average of the 2 highest frequencies (2000 and 4000 Hz octave bands)
41_2F	Average of 2 medium frequencies (500 and 1000 Hz octave bands)

It was found (Appendix E) that there is no clear evidence to support the use of a particular method of averaging. Among the literature available regarding concert hall acoustics, the frequency bands of 500 and 1000 Hz are sometimes used to achieve an averaged single number index (Tachibana and Yamasaki 1993; Chiang 1994). However, no justification was found to use a similar approach in this particular analysis. Therefore, in order to represent each church acoustic measure by a single number, an average of all six octave frequency band values (125 to 4000 Hz) was adopted.

3.2.3.2 Results

The relationships among the acoustical measures in a scatterplot matrix (casement plot) are presented in Figure 3.2 using only 41 points (one for each church), with the all frequencies option of averaging. Each case shows 41 data-points (41 churches). The corresponding correlation coefficients are displayed in Table 3.5. Table 3.5 presents the absolute values for the correlation coefficients (R) regarding the relationships among the six acoustical measures. For each case there are two R values shown ($|R_{linear}|$ [$|R_{best\ fit}|$ smooth). The R_{linear} (left) used the linear regression model and the $R_{best\ fit}$ (right) used the best-fit model obtained from all of the tests (linear, logarithmic, cubic, exponential or quadratic). The equations for each of the best fit regression lines are shown in Table 3.6.

TABLE 3.5 - Correlation coefficients ($|R_{linear}|$ [$|R_{best\ fit}|$ smooth) among acoustical measures (w/ averaged data-all frequencies).

Measure	RT	EDT	C80	D	TS
EDT	0.999[**0.999**lin	-	-	-	-
C80	0.90[**0.97**log	0.90[**0.97**log	-	-	-
D	0.80[**0.84**log	0.80[**0.85**exp	0.97[**0.97**lin	-	-
TS	0.99[**0.99**lin	0.995[**0.995**lin	0.92[**0.99**log	0.84[**0.94**log	-
L	0.26[**0.32**exp	0.26[**0.32**exp	0.33[**0.36**cub	0.25[**0.32**qua	0.27[**0.31**log

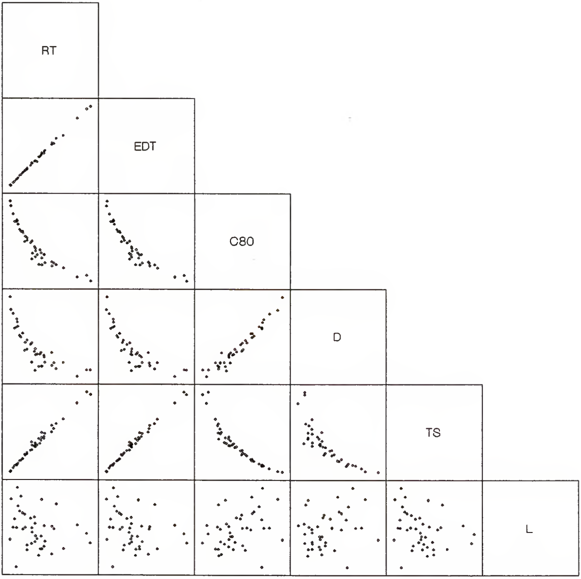


Figure 3.2 - Scatterplot matrix (casement plot) for the relationships among the six acoustical measures with room average data (1 point/church).

TABLE 3.6 - Best fit equations among acoustical measures (w/ averaged data - all frequenc.).

$RT = -0.0010 + 1.047\ EDT$	$EDT = 0.837 + 11.362\ e^{-7.574\ D}$
$RT = -1.853 - 3.396\ \log_n (D)$	$EDT = -0.173 + 0.014\ TS$
$RT = -0.179 + 0.015\ TS$	$D = 1.274 - 0.194\ \log_n (TS)$
$C80 = 2.868 - 5.49\ \log_n (RT)$	$D = 0.363 - 0.025\ L + 0.0011\ (L)^2$
$C80 = 2.605 - 5.48\ \log_n (EDT)$	$L = 11.969 + 8.902\ e^{-0.632\ RT}$
$C80 = -9.612 + 27.574\ D$	$L = 12.093 + 9.361\ e^{-0.722\ EDT}$
$C80 = 27.978 - 5.822\ \log_n (TS)$	$L = 22.915 - 2.504\ \mathrm{Log}_n (TS)$
$C80 = -4.099 + 0.0004\ (L)^3$	

The highest correlations are now stronger than when using all the available data (the 2030 points). The (remarkably) highest correlations are now between RT and EDT ($|R|$ = 0.999), EDT and TS ($|R|$ = 0.995), RT and TS ($|R|$ = 0.993) or D and C80 ($|R|$ = 0.969); The correlations between L and the other measures are now not as low as in the previous situation (all points) but nevertheless still markedly low ($|R| < 0.37$) maintaining a non-significant relationship among them.

Nonlinear models seem to give a slightly better prediction line than the linear models in the majority of the cases studied (70%). Among these, the logarithmic smooth presents a better fit in many cases, especially those regarding the C80 measure. This is due to the logarithmic mathematical characteristic of many of the measures by their definition.

It was found that there are significant differences between the $|R|$ results (1 to 68% higher $|R|$ in the averaged data option) for the all data and averaged data approaches used in this study. Depending on the situation in study (a single point measure or a room averaged value) the corresponding prediction equation should be used.

3.2.4 Bass Ratios

The bass ratios were calculated using all data with the two sound source location's results (Appendix F). Figure 3.3 shows the relationship between bass ratios calculated by the two methods described above. Table 3.7 summarizes simple statistics of the bass ratio data

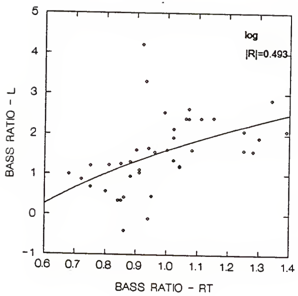


Figure 3.3 - Relationships of bass ratio regarding loudness vs. bass ratio regarding reverberation time with log. smooth (41 points = 41 churches).

associated with the 41 churches. Table 3.8 gives the Pearson correlation coefficients between BR_RT and the six acoustical measures. The results shown in Table 3.8 do not present any strong linear relationship among the parameters tested. However, these two parameters are important because they are two more to be used in the statistical analyses with the architectural parameters. They are usually associated with the subjective quality of warmth (Beranek 1962; Chiang 1991).

TABLE 3.7 - Simple statistics of the bass ratios for the 41 churches.

Measure	MINIMUM	MEAN	MAXIMUM
BR_RT	0.68	0.98	1.39
BR_L	- 0.40	1.52	4.21

TABLE 3.8 - Pearson correlation matrix (using all six frequency bands in the average).

R	RT	EDT	C80	D	TS	L
BR_RT	0.288	0.296	- 0.285	- 0.305	0.296	0.441
BR_L	- 0.041	- 0.047	0.091	0.070	- 0.040	0.501

3.3 Church Variations

3.3.1 Within Church Differences

A very simple measure of the spatial variation of the acoustical measures within each church is the standard deviation of the room average value. This standard deviation includes both the seat variation (by moving the receiver) as well as the sound source position (altar or congregation locations). The Figure 3.4 presents the analysis regarding the within church variation for all frequency bands and source/receiver locations. For each church (numbered from *1* to *41* as in the Table 2.1) and for each acoustical measure, the mean value is presented together with a standard deviation, two sided interval. The spatial variation of measured RT and EDT values is much smaller than that of C80 or D. Especially in small churches, where

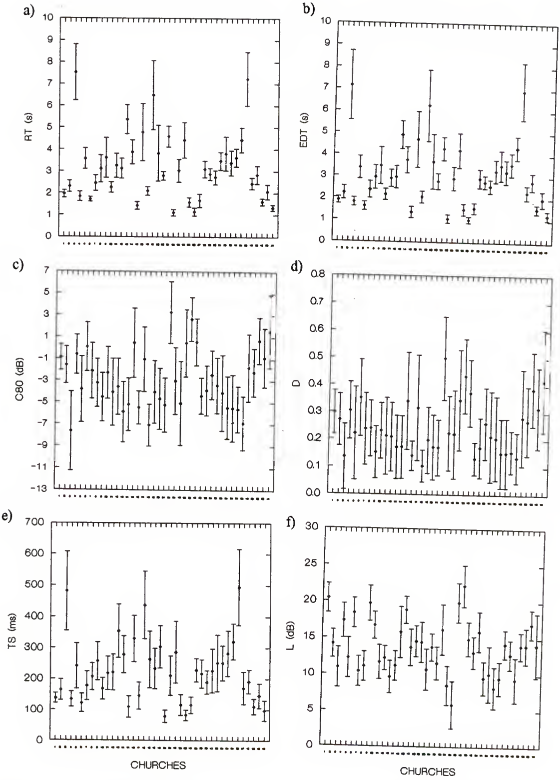


Figure 3.4 - Within variation of the six acoustical measures in each church (the x axis shows the 41 churches numbered 1 to 41 from left to right). Mean values with one standard deviation confidence interval.

a) RT; b) EDT; c) C80; d) D; e) TS; f) L.

the effect of air absorption at high frequencies is very small, RT and EDT values vary very little throughout the rooms. The larger standard deviations occur in the biggest churches. The variation of EDT values is a little larger than the ones with the RT values. The standard deviation of C80 and D values indicate that there are very large within church differences.

Figure 3.5 displays the 41 church mean values and the spatial standard deviation of the measured values in each room for each acoustical measure. Those Figures are summarized in Table 3.9 that presents simple statistics of the 41 means and standard deviations.

TABLE 3.9 - Simple statistics of the data from the 41 church sample.

Measure	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)
Mean (of 41 means)	3.2	3.0	- 2.9	0.25	221	13.6
Mean (of 41 st. dev.)	0.5	0.5	2.5	0.13	55	2.5

Using these Figures and Table it can be seen that RT values vary very little throughout these churches (a mean standard deviation of 0.5 s in a RT mean of 3.2 s). EDT values follow a similar pattern but with a small increase in the relative importance of the standard deviation over the mean values. The standard deviation of L values are very similar among themselves (around 2.5 dB) for an average of 13.6 dB. The extreme cases, regarding the spatial variation within churches are the D values and the C80 data. The standard deviation of C80 values was found to be around 2.5 dB when the mean values are near -3 dB. This analysis suggested that the magnitude of church standard deviations may be determined by the receiver architectural parameters.

In order to compare the magnitude of variations of the church spatial standard deviations among the six acoustical measures, a new measure was calculated. For each church, the room standard deviation of the acoustical measure was compared to a reference value. This reference value was chosen as the standard deviation of the 41 mean values

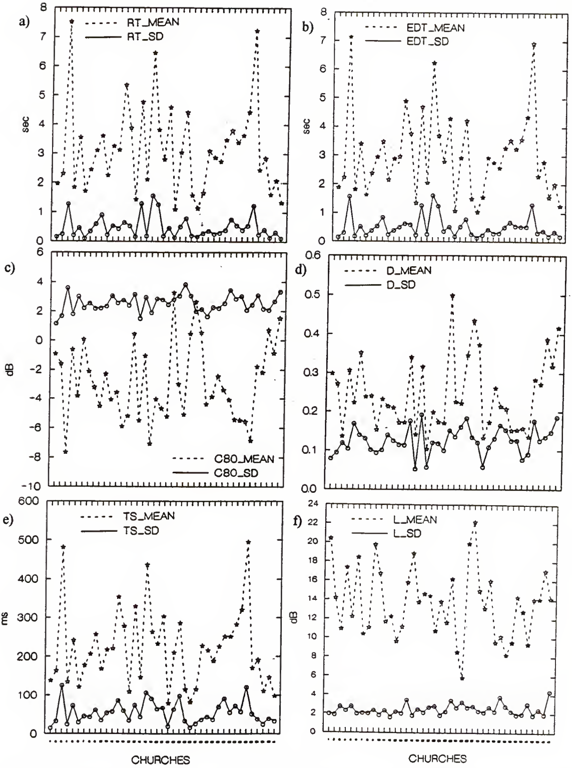


Figure 3.5 - Standard deviation (_SD) compared with mean values (_MEAN) for each church (the *x* axis shows the 41 churches numbered 1 to 41 from left to right) for the six acoustical measures.
a) RT; b) EDT; c) C80; d) D; e) TS; f) L.

calculated for the corresponding acoustical measure being analyzed. Figure 3.6 compares these relative standard deviations. Table 3.10 presents simple statistics regarding the relative standard deviation values.

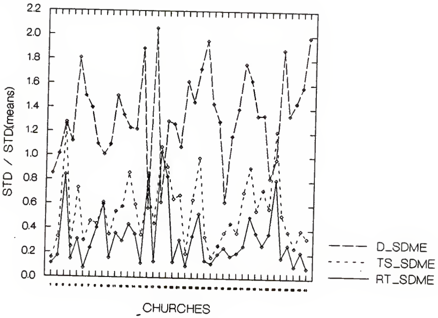
TABLE 3.10 - Simple statistics regarding the relative standard deviation divided by the overall standard deviation of the 41 means [STD/STD(means)].

Measure	RT	EDT	C80	D	TS	L
Minimum	0.07	0.10	0.44	0.57	0.16	0.45
Mean	0.33	0.36	0.95	1.34	0.55	0.67
Maximum	1.03	1.11	1.44	2.06	1.26	1.19
Range	0.96	1.01	1.00	1.49	1.10	0.74

Using these Figures and Table 3.10 it can be stated that the RT has the smallest spatial within church variation among the six acoustical measures tested, closely followed by EDT. The largest spatial within church variation was found in the C80 and D data, having up to four times more spatial variation than the RT data. The average church standard deviations varied from 33% to 134% of the standard deviation of the overall 41 means, over the six acoustical measures. The smallest range of relative church standard deviations was found for the acoustical measure L.

Figure 3.7 presents the within church variation analyzed by frequency bands for two extreme cases - Church 3 (volume = 18700 m^3) versus Church 22 (volume = 2500 m^3). Church 3 data are typical of a large church (with RT values decreasing in the higher frequency bands, due to air absorption) with wide standard deviation confidence intervals. Church 22 data are typical of a small church with very small confidence intervals (and no significant variation in the RT for the higher frequency bands). With this pairwise example, differences can be traced to the size of churches. The variation of RT, EDT and TS is very small at all frequencies bands in Church 22 but in Church 3 a larger standard deviation is found,

a)



b)

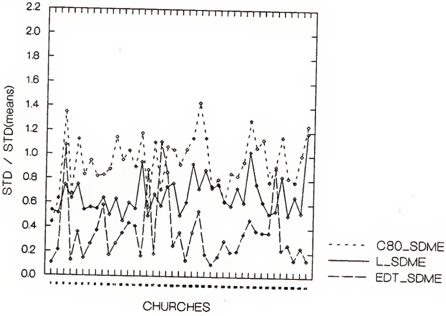


Figure 3.6 - Comparison among room relative standard deviation (SDME = room standard deviation / standard deviation of the 41 means).
a) Comparisons for RT, D and TS; b) Comparison for EDT, C80 and L.

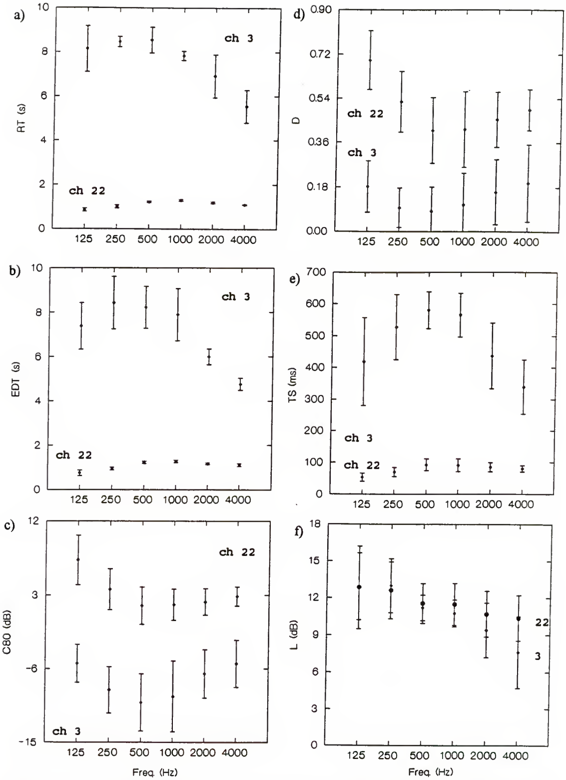


Figure 3.7 - Comparative example of within church variation analyzed by frequency bands. Mean values are shown with one standard deviation confidence interval. Church 3 (*Bas. Estrela*, Lisboa - Neoclassic) vs. Church 22 (*Sta. Clara*, Porto - Baroque).
a) RT; b) EDT; c) C80; d) D; e) TS; f) L.

decreasing in higher frequencies due to air absorption. The standard deviation of C80 and D data do not show significant differences between the two churches. The spatial variation of measured values is very similar for both churches except in the 4 kHz band where, again, the effect of air absorption in the larger churches appears.

In general, the spatial variation in the churches show important similarities. Nevertheless there are some differences among churches that may be attributable to the characteristics of each room, especially their differences in size.

3.3.2 Among Church Differences

Figure 3.8 presents the analysis regarding the differences among churches. For each church (numbered from *1* to *41* as in the Table 2.1) and for each acoustical measure, the mean value is presented together with one standard error two sided interval. The standard error interval was used here and not the standard deviation because different means of different churches are compared. For that reason the standard error of the measured mean has more significance than the standard deviation (sd) because the sd measures the variation among the values of one room, not the variation of the mean in different rooms. Table 3.11 presents the range (max. value - min. value) of the 41 means concerning the six acoustical measures.

TABLE 3.11 - Range of the 41 means (all churches) for the six acoustical measures.

Measure	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)
Range (of 41 means)	6.4	6.1	10.9	0.40	416	16.4

The church averages, shown in Figure 3.8 indicate very large inter church variation, clearly significant in most the cases for RT, EDT, C80, TS and L. Only D data does not follow this clear trend perhaps due to the larger within room variation of this measure.

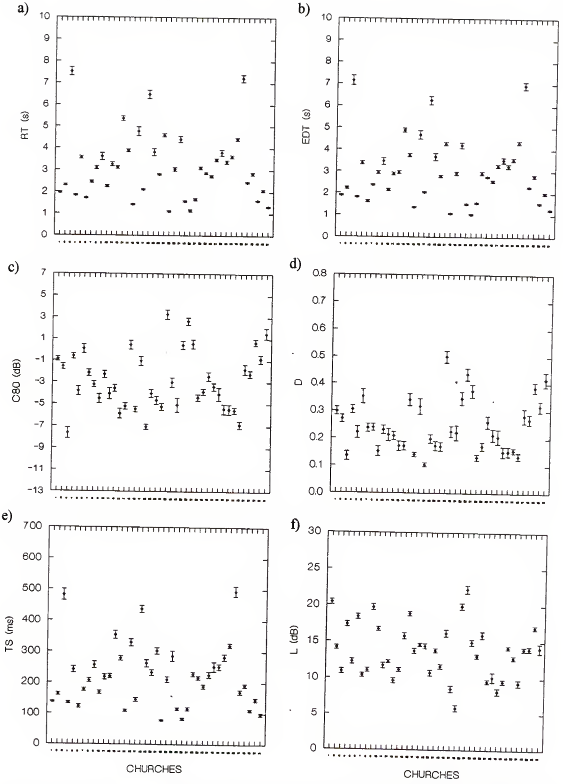


Figure 3.8 - Mean values of acoustical measures with one standard error confidence interval for each church (numbered 1 to 41 from left to right on the x axis).
a) RT; b) EDT; c) C80; d) D; e) TS; f) L.

The inter church differences shown in Figure 3.8 were tested to determine whether they were statistically significant. ANOVA (ANalysis Of VAriance) tests with Tukey's HSD multiple comparion tests were done to verify whether the differences between church means are significant relative to the amount of variance within each room. The tests were done in 510 pairs of churches, randomly selected out of a total of a maximum possible of 820 different pairs of churches among all the 41 churches in the sample. Therefore a sample of 62% of the total number of pairs was used. In many of the cases especially for RT, there was a statistically significant effect of the church on the acoustical mean values as seen in Table 3.12. Only the values for the measure D show a significant similarity among churches by which slightly less than half of churches were different. Only 45% of the pairs of means tested were statistically different. While many of the differences between churches were statistically significant at a p-value level of 0.05, these tests did not determine if these differences are perceived by listeners in the rooms. Figure 3.76 presents the inter church variation for two extreme cases (Church 3 vs. Church 22), where a similar conclusion can be drawn for the statistically significant differences between data.

TABLE 3.12 - ANOVA tests regarding inter-church variation among six acoustical measures (p-value < 0.05).

Number of inter-church mean differences found statistically significant out of 510 pairs tested					
RT 410 (80%)	EDT 398 (78%)	C80 312 (61%)	D 227 (45%)	TS 369 (72%)	L 382 (75%)

3.4 Sound Source Position

3.4.1 General Analysis

As mentioned earlier, two sound source locations were used. In the Altar location the sound source was positioned near the main altar. In the Congregation location the sound

source was positioned in the middle of the congregation seating area on the main longitudinal axis of the church (central nave). In both cases the loudspeaker was positioned at approximately 0.8 m from the floor. Figure 3.9 offers the behavior of the data regarding both sound source locations. These Figures show the mean values of each acoustical measure with a one standard error confidence interval. A two-sample t test was performed comparing the data grouped by those two sound source positions (ALTAR and CONGREGATION). The results of the statistical analysis in which Ho: $\mu_{ALTAR} = \mu_{CONGREGATION}$ (the means are equal) and Ha: $\mu_{ALTAR} \neq \mu_{CONGREGATION}$ (the means are different) are presented in Table 3.13.

TABLE 3.13 - Probability-values for each acoustical measure regarding the sound source position - Altar vs. Congregation. Values < 0.05 indicate statistically significant differences between positions.

Probability-values controlling for sound source position (Altar vs. Congregation)					
RT	EDT	C80	D	TS	L
0.5070	0.2420	0.0000	0.0000	0.0003	0.0000

For all measures, except RT and EDT, the two-sample t test does not support the idea to reject the alternative hypothesis (Ha). Therefore there is statistical evidence to support the conclusion that the sound source position (Altar or Congregation) affects the mean values of C80, D, TS and L but not for the mean values of RT and EDT.

3.4.2 Church by Church Analysis

The same two-sample t test analysis was performed to compare both sound source positions in each of the 41 churches (Appendix G). The number of churches where pr. > F < 0.05 for the test are summarized in Table 3.14. There were only 1 and 2 churches where statistically significant differences were found for acoustical measures RT and EDT, respectively. For the RT and EDT data there were no statistical evidence to support the idea

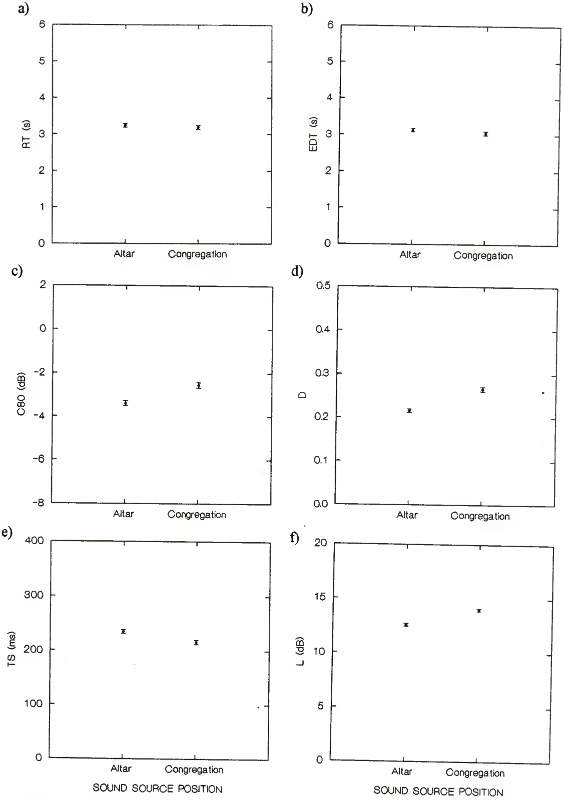


Figure 3.9 - Effect of sound source position (Altar vs. Congregation) on the values of six acoustical measures. Mean values with one standard error confidence interval are shown. a) RT; b) EDT; c) C80; d) D; e) TS; f) L.

of differences among their mean values due to different sound source positions within churches. For the C80, D and L data, 40 to 55% of the churches had statistically significant differences in the mean values of acoustical measures made from the two different source locations.

TABLE 3.14 - Analysis between two sound source positions. Summary of *t* tests.

Sound Source Position	Number of churches in each situation					
Altar vs. Congregation	RT	EDT	C80	D	TS	L
With Significant Differences	1	2	17	16	12	22
No Significant Differences	40	38	24	25	29	19

3.5 Architectural Styles

3.5.1 General Analysis

The hypothesis tested concerned the effect of architectural styles and their evolution through time on these six acoustical measures. The 41 churches tested were grouped, according to their main interior architectural features (Azevedo 1985; DGEMN 1936/64; Gil 1992) in eight architectural styles. When several styles could be identified in the same church, only the most significant for the overall acoustic impression was considered (see Table 2.1).

3.5.1.1 Acoustical measures

Table 3.15 displays the mean values of the acoustical measures controlling for the architectural styles. Figure 3.10 presents the analysis of the acoustical measures regarding the architectural styles, chronologically ordered (from 1-Visigothic to 8-Contemporary) with a standard error interval using one point which is the average of all six frequency bands for each church (41 points). In those graphs, trends are clearly visible. RT, EDT and TS increase until style *5* and then decrease to style *8*. C80 and D decrease until style *5* and then increase

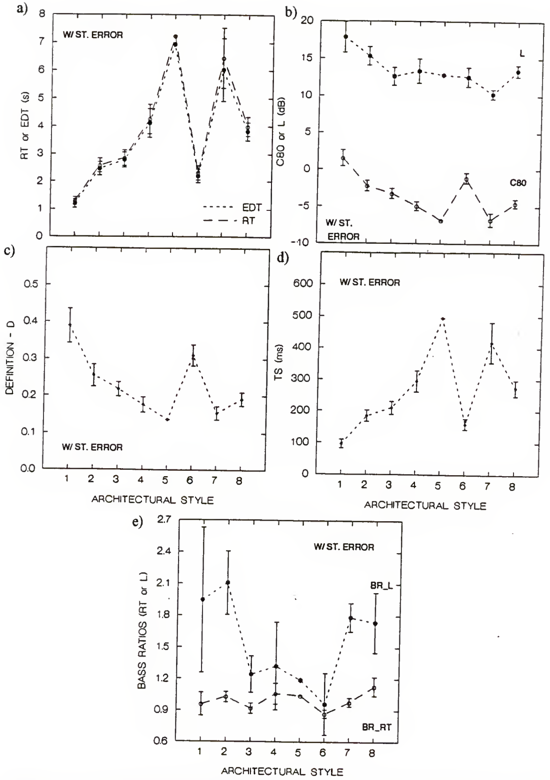


Figure 3.10 - Averaged data for eight acoustical measures with one standard error confidence intervals plotted vs. the architectural styles in chronological order from left to right (1-Visigothic, 2-Romanesque, 3-Gothic, 4-Manueline, 5-Renaissance, 6-Baroque, 7-Neoclassic, 8-Contemporary).
a) RT and EDT; b) C80 and L; c) D; d) TS; e) BR_RT and BR_L.

to style *8*. L, BR_RT and BR_L do not present the same clear behavior. The break point in time where the general trend of the data changes is the period of the Protestant and Catholic Reformations where speech in Catholic churches became more important than it had been previously. The liturgical music also changed during this time. This can be a coincidence or an important acoustical change. Style *6* (Baroque) radically changed the acoustical behavior of the churches tested. Those changes seem to be soon forgotten. With the Neoclassic the previous trend of increasing RT, EDT and TS (or decreasing C80 and D) reappears perhaps due to the wave of antimodernism rules in the Church following the French Revolution, having a new positive attitude towards the past. That trend was inverted only in this century, where speech is perhaps the most important part of the religious services.

TABLE 3.15 - Mean values of acoustical measures (all freq.) controlling for architectural style.

Architectural Styles	Mean Values *					
	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)
1 - Visigothic	1.3	1.2	1.5	0.39	96	17.9
2 - Romanesque	2.6	2.5	-2.3	0.25	184	15.3
3 - Gothic	2.8	2.8	-3.3	0.22	210	12.6
4 - Manueline	4.2	4.1	-4.9	0.18	294	13.3
5 - Renaissance	7.2	6.9	-6.9	0.14	495	12.8
6 - Baroque	2.3	2.2	-1.1	0.31	159	12.6
7 - Neoclassic	6.4	6.0	-6.8	0.15	418	10.4
8 - Contemporary	4.0	3.8	-4.5	0.19	273	13.4

* average of all six octave frequency bands

The change in the acoustics of churches with the Baroque style can be perhaps explained by the large amount of ornamentation that began being used, especially in the wood-carving covering very large interior surfaces and the wide use of highly decorated lateral chapels. This general increase in ornamentation can be justified as a move to impress the congregations and to attract them to the Catholic Church against the appealing approaches from new denominations. Also the size and shape of churches evolved from the forms that

were common in the previous styles to a more human dimension with not so large volumes and tall ceilings.

3.5.1.2 Music and reverberation time

The reverberation time values seem to increase through time with the highest RT occurring around the 16th-17th centuries (Figure 3.10a). This coincides with the increased use of the organ in church music where a longer RT is desired. In early days, organs, which are known to have been used for other purposes before the second century BC, were banned from all churches because of their association with pagan rites and gladiator combats (Briggs 1946). However they were progressively adopted after the 10th-11th century. Longer RT and EDT appear when church choirs grew in size. The Papal Choir in Rome increased from 10 to 24 singers in the late 15th century (Kamien 1988). Church music in the Renaissance changed from being sung by several soloists to being performed by an entire (male) choir (Kamien 1988). It is during this period when professionals, many of whom were organ composers, had the control of church music (16th-17th centuries) like Desprez, Palestrina, Gabrieli and later Bach. They took advantage of the reverberant conditions found in churches in the music they composed. For example Gabrieli and Buxtehude used the rich and rolling sound of counterpoint in a reverberative nave when they composed music to be performed in St. Mark's in Venice or St. Mary's church in Lübeck. The Council of Trent (1563) decreed that church music should be composed not to give empty pleasure to the ear but to inspire religious contemplation. This was during the time of the Counter Reformation and the corresponding changes in the RT and EDT values found in churches (or increase in the C80 and D values) seemed to follow those changes. For instance, the Bach cantatas which were composed for St. Thomas Church in Leipzig had its emphasis on the understanding the sung narrative and the devotional texts, using to advantage the moderate reverberation time of that

church. Today, where new organs in new churches are not common and when speech intelligibility is fundamental after the Second Vatican Council, the RT and EDT values seem to decrease to adjust to these new requirements. Contemporary churches are moving towards the acoustical conditions of early churches perhaps in part for the same reason: different musical instruments (less organ) are used.

3.5.2 ANOVA Tests

3.5.2.1 All points

The results of ANOVA tests done with all points available (all frequency bands and all source/receiver locations) are shown in Table 3.16. Perhaps due to the large number of points involved and the corresponding high degrees of freedom, and for a p-value at 0.05 level, almost all (153 out of 168 cases) are statistically different. That is, each acoustical measure/style value is statistically different from all the others with few exceptions.

TABLE 3.16 - ANOVA tests regarding architectural styles vs. acoustical measures (all points).

RT	27 style differences found statistically significant (p-value < 0.05) out of a total of 28 (96 %)
EDT	28 style differences found statistically significant (p-value < 0.05) out of a total of 28 (100 %)
C80	27 style differences found statistically significant (p-value < 0.05) out of a total of 28 (96 %)
D	21 style differences found statistically significant (p-value < 0.05) out of a total of 28 (75 %)
TS	28 style differences found statistically significant (p-value < 0.05) out of a total of 28 (100 %)
L	22 style differences found statistically significant (p-value < 0.05) out of a total of 28 (79 %)

3.5.2.2 41 points

The results of ANOVA tests with Tukey HSD multiple comparison tests done with only 41 points, one mean value for each church, are presented in Appendix H and summarized in Tables 3.17 and 3.18. In these Tables two approaches were followed: using all pairwise comparisons among architectural styles and only regarding consecutive architectural styles (Table 3.17 or 3.18 respectively). The summary of this analysis is presented in these Tables.

TABLE 3.17 - Summary of the results of ANOVA tests regarding architectural styles vs. acoustical measures (averaged data for each church - all pairs). Number (and %) of style differences found statistically significant (P-value < 0.05) out of a total of 28 pairs.

RT	EDT	C80	D	TS	L
12 (43%)	12 (43%)	6 (21%)	2 (7%)	13 (46%)	0 (0%)

The results of the ANOVA tests done with averaged data (41 points for each acoustical measure - one for each church) for consecutive architectural styles are presented in Table 3.18. The goal was to verify if there were statistically significant differences among each of the eight acoustical measures in consecutive architectural styles. These results confirm that there is statistical evidence to support the hypothesis of differences in some of the acoustical measures in consecutive architectural styles especially RT, EDT and TS. These differences appear in the last five styles, that is, after the 14th century. RT and EDT appear most suitable to identify differences among architectural styles. These are also the two acoustical measures of the nine studied that are perhaps the most useful to rate the overall acoustical quality of churches for music especially church organ music (Berry and Kinzey 1954; Rienstra 1957; Doelle 1972; Rettinger 1977; Marshall et al.; Moore 1988; Egan 1988).

TABLE 3.18 - ANOVA tests regarding architectural styles vs. acoustical measures. The number of consecutive architectural style differences found statistically significant (p-value < 0.1) out of a maximum total of seven (style *1* vs. *2,* style *2* vs. *3*, ... , style *7* vs. 8) are listed.

RT	EDT	C80	D	TS	L	BR_RT	BR_L
4	4	1	0	3	0	0	0

3.5.3 Standard Deviation versus Standard Error

Another important subject to discuss is, again, the use of the standard deviation or the standard error confidence intervals. There are situations where one option has clear advantages against the other and stronger statistical implications. The use of the standard error

was again chosen because in this situation, a mean or an interval representative of one acoustic measure was desired for one architectural style (Figure 3.10). Therefore, a standard error of that mean is preferred. If one wanted to look to one receiver position in a particular church of a specific architectural style and to predict its own acoustic measure or confidence interval for that measure the standard deviation data would be more useful and significant.

3.6 Classical Diffuse Field Theory

The classical diffuse field theory can be used to define certain relationships among acoustical measures (Gade 1991). A sound field is considered diffuse if the amplitudes and phases of the sound waves are uniformly distributed over all directions. Therefore in a diffuse sound field the sound energy is uniformly distributed in the room and the sound decay is exponential (Kuttruff 1991). Using all data (all frequencies at all source/receiver locations - 2030 points), experimental equations derived from the diffuse field theory were tested and the results found are shown in Table 3.19.

TABLE 3.19 - Diffuse field theory vs. current experimental equations in churches (with 2030 points).

DIFFUSE FIELD THEORY EQUATIONS	EXPERIMENTAL EQUATIONS	R^2
$EDT_{exp} = RT$	$EDT = 0.941\ RT + 0.043$	0.972
$TS_{exp} = RT / 0.0138$	$TS = RT / 0.0150$ $TS = RT / 0.0156 + 17.821$	0.823 0.828
$C80_{exp} = 10 \log_{10} (e^{1.104/RT} - 1)$	$C80 = 10 \log_{10} (e^{1.152/RT} - 1.004)$ $C80 = 1.407 * 10 \log_{10} (e^{1.041/RT} - 0.856)$	0.567 0.572
$L_{exp} = 10 \log_{10} (RT/V) + 45$	$L = 10 \log_{10} (RT/V_{Total}) + 44.635$ $L = 10 \log_{10} (0.932\ RT/V_{Total}) + 44.942$	0.645 0.645

Note: exp - expected

As seen in Table 3.19, the classical diffuse field theory explains the relationships between RT and EDT fairly well but can not justify more than 57% of the variance between

C80 and RT. The remaining part of the variance may be able to be explained by adding some architectural parameters to the models.

Naturally, churches are only partially diffuse rooms because neither the absorption nor the sound sources are evenly distributed over the area, and the interior surfaces are not perfectly diffusing. Nevertheless churches are closer to being a diffuse room than concert halls and auditoria usually are. This is due to the larger number of sound source positions in churches where the congregation can be considered as multiple sound sources, small differences in the absorption usually found among different areas of the churches and the high degree of diffusion found on the walls of the churches provided by the existence of columns, lateral altars, and other large religious ornamentation such as statues, shrines, etc. In many churches these are at a scale that provide more diffusion than in a typical concert hall at least in several frequency bands.

3.7 Summary

Relationships among the acoustical measures were defined and prediction equations were calculated to estimate measures taken at individual locations within each room as well as the mean values in each church. It was found that nonlinear models give a slightly better prediction than the linear models in 70% of cases studied. Among these, the logarithmic smoothing presents a better fit in some cases, especially in those with the C80 measure. This is due to the logarithmic mathematical characteristic of many of these measures.

There are significant differences between the correlation coefficient R results (1 to 68% higher |R| in the averaged data option) depending upon whether all the data or just room averaged data were used. Depending on the situation in study, a single point measure or a room averaged value, the corresponding prediction formula should be used.

Three groups of related acoustical measures were found in this study: RT/EDT/TS, C80/D and L. RT and EDT present a very high correlation ($|R| > 0.99$) as expected because they are very similar quantities with comparable physical meaning. EDT and TS also show a strong relationship between them ($|R| > 0.94$). These two factors suggest that any of those three measures (RT, EDT or TS) can be used to predict the other two. The RT appears as the reasonable choice due to its clear physical meaning and traditional use in this area. However EDT is considered to be a better predictor of the sense of reverberance and is more useful if subjective analysis is desired. C80 and D are highly correlated ($|R| > 0.94$) mainly due to their comparable physical and mathematical design. The correlation between L and the other five measures is markedly low ($|R| < 0.37$) confirming the individuality of this measure among those six and indicates that this quantity should be included as one of the acoustical measures. From the acoustical measures used, the most significant or useful to characterize the acoustical environment of churches are: RT (or EDT if subjective studies are involved), C80 and L.

Within and among church differences in the data for the six acoustical measures and the effect of sound source position were also analyzed. The within church variation in RT and EDT data were found to be much smaller than the variation of other measures. This variation was four times smaller than the variation of C80 or D measures. This agrees with the findings of similar studies made in concert halls (Barron 1994). In general, the spatial variation in the acoustical measures made in churches show important similarities among all rooms. Nevertheless, there are differences among churches that may be attributable to the architectural characteristics of each room, especially to differences in size. It was found that the differences among the mean values of the acoustical measures made in churches were significant in nearly 80% of the cases for the RT and EDT data and 61% to 75% in C80, TS and L data. However, there were only significant differences in the mean values of D in less than half of

the churches because the within church spatial variation of their values were relatively higher than the spatial variation of other measures. Therefore RT was found to be the most significant single measure to characterize a church as in concert halls (Barron 1994).

The churches of this sample were grouped in eight architectural styles. From the acoustical measures tested, conclusions were drawn on the effect of the evolution of the architectural styles through the last fourteen centuries. In general this study suggests that some changes in the acoustical measures made in churches are related to changes in their architectural styles. Statistically significant differences were found in churches regarding their architectural styles for the RT, EDT and TS measures and a visible trend seems to be present in their variation through time. An increase in the RT (or EDT) mean values was found through the first five styles with a decrease in the Baroque style (Reformation period) and again a negative slope in the last two styles (the Vatican II period). The TS data behave similarly but with inverted slopes due to its physical characteristics. Changes in church music and other church practices and changes in the mean values of some acoustical measures seem to have occurred in the same historical periods. RT and EDT appeared as the most suitable acoustical measures to identify differences in churches regarding their architectural styles.

CHAPTER 4
RELATIONSHIPS BETWEEN ACOUSTICAL MEASURES AND ARCHITECTURAL PARAMETERS

4.1 Purpose

Many of the previous results indicate that the variations found among churches may be explained by the effects of the architectural parameters. Therefore the purpose of this Chapter is to analyze how architectural features of this type of building relate with the acoustical measures and to answer the second group of research questions as stated in Chapter 1.

4.2 Architectural Parameters

The architectural parameters were primarily chosen based on the analysis from well accepted earlier studies in the field of concert hall acoustics (Barron and Lee 1988; Bradley 1989; Gade 1990; Hook 1989). Fifteen architectural parameters were used as seen in Table 4.1. Appendix I and Table 4.2 present the results of the relationship analyses and a summary with simple statistics regarding the fifteen architectural parameters for each church tested.

Table 4.3 and Figure 4.1 present the relationships among architectural parameters using a scatterplot matrix (casement plot) and the Pearson correlation coefficients. As seen in those two illustrations, the great majority of the fifteen architectural parameters are independent and not significantly related to each other. This enables one (in a simple way) to use them as a realistic sample of architectural parameters to characterize the 41 churches.

Figure 4.1 - Relationships among architectural parameters using a scatterplot matrix - casement plot (41 points = 41 churches).

TABLE 4.1 - Description of the architectural parameters used.

TERM	DEFINITION
VOL_TOT	Volume Total (m^3)
VOL_NAVE	Volume Nave (m^3)
AREA_TOT	Area Total (m^2)
AREA_NAV	Area Nave (m^2)
L_MAX	Length Maximum (m)
L_NAVE	Length Nave (m)
H_MAX	Height Maximum (m)
H_NAVE	Height Nave (m)
VTO_ATO	Height Total average(m) [= Volume total / Area total]
W_NAVE	Width Nave (m)
W_AVG	Width average (m)
SEATS	Number of Seats
ALPHA	Absorption Coefficient [α average value for all surfaces]
ABSO_TOT	Total Absorption (m^2)
R_LOCAL	Constant of the room [$R = A / (1 - \alpha_{avg.})$]

Note: *NAVE* stands for the entire church excluding lateral chapels and main altar (apse)
TOTAL stands for the entire church including lateral chapels and main altar (apse)

TABLE 4.2 - Summary table for the 15 architectural parameters with simple statistics.

Architectural Parameters	MIN.	MEDIAN	MEAN	MAX.	SKEWNESS	KURTOSIS
VOLUME total (m^3)	299	3918	5772	18674	0.99	0.01
VOLUME nave (m^3)	250	3386	4747	15936	0.99	-0.03
AREA total (m^2)	56	427	450	1031	0.41	-1.07
AREA nave (m^2)	42	333	353	781	0.36	-1.21
LENGTH maximum (m)	11.5	30.8	33.1	62.2	0.31	-0.77
LENGTH nave (m)	8.3	22.7	24.4	42.3	0.26	-1.00
HEIGHT maximum (m)	6.5	13.4	14.8	39.0	1.67	3.47
HEIGHT nave (m)	5.8	10.9	12.0	26.0	0.88	0.38
HEIGHT total avg.* (m)	5.3	10.2	11.2	22.7	0.69	-0.14
WIDTH nave (m)	3.6	11.0	13.0	37.5	1.31	2.47
WIDTH average (m)	5.0	13.0	13.6	36.8	1.11	1.80
SEATS	0	210	240	623	0.60	-0.46
ALPHA average	0.030	0.062	0.073	0.230	2.68	7.82
ABSORPTION total (m^3)	13.7	130.5	170	962	2.81	10.82
R_LOCAL (m^2) **	14.4	136	189	1222	3.36	14.52

NOTES: * VOLUME total / AREA total ** ABS. total / (1 - ALPHA.avg)
SKEWNESS - Measure of asymmetry - Positive: long right tail, Negative: long left tail
KURTOSIS - Measure of normality - Signif. greater than zero: the variable is longer tailed than a normal distribution

TABLE 4.3 - Pearson correlation coefficients among the 15 architectural parameters. R > 0.95 are bold faced.

	SEA TS	VOL TOT	VOL NAV	A TO TAL	A NAV	L MX	L NAV	H MAX	H NAV	W NAV	W AVG	VTO ATO	ALP AVG	R L OCA
VOL_TOT	0.739	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL_NAVE	0.742	**0.991**	-	-	-	-	-	-	-	-	-	-	-	-
AREA_TOT	0.822	0.915	0.905	-	-	-	-	-	-	-	-	-	-	-
AREANAVE	0.847	0.863	0.876	**0.977**	-	-	-	-	-	-	-	-	-	-
L_MAX	0.685	0.877	0.841	0.850	0.774	-	-	-	-	-	-	-	-	-
L_NAVE	0.746	0.913	0.906	0.909	0.877	0.950	-	-	-	-	-	-	-	-
H_MAX	0.599	0.832	0.838	0.648	0.603	0.691	0.684	-	-	-	-	-	-	-
H_NAVE	0.456	0.792	0.790	0.566	0.485	0.715	0.690	0.902	-	-	-	-	-	-
W_NAVE	0.656	0.397	0.436	0.640	0.719	0.270	0.385	0.298	0.129	-	-	-	-	-
W_AVG	0.752	0.520	0.553	0.739	0.814	0.361	0.485	0.391	0.188	**0.973**	-	-	-	-
VTO_ATO	0.515	0.823	0.820	0.605	0.542	0.754	0.741	0.902	**0.978**	0.139	0.215	-	-	-
ALPHA_AV	0.170	0.027	0.048	0.079	0.111	0.040	0.115	-0.048	0.021	0.180	0.095	0.040	-	-
R_LOCAL	0.569	0.606	0.629	0.641	0.657	0.560	0.664	0.367	0.412	0.372	0.424	0.447	0.655	-
ABSORPTIO	0.608	0.667	0.685	0.704	0.710	0.618	0.718	0.415	0.453	0.403	0.462	0.491	0.613	**0.996**

4.3 Relationships between Acoustical Measures and Architectural Parameters

4.3.1 The Search for a Representative Single Number Average

With the fifteen architectural parameters described earlier and used in this study there is a need for a corresponding single number acoustical measure that is representative of each church. A single-number for each acoustical measure is now essential to be able to compare to the correspondent architectural parameter in the same church. So far, the average of all six octave frequency bands has been used but perhaps it is not the best single-number possible for the purpose of this particular analysis. Therefore, the same seven frequency averaging options, as presented in Table 3.4, were again tested in this particular situation using simple linear models and general linear models (Appendix J). The results found support the use of only the 500 Hz and 1000 Hz octave frequency bands in the following analyses.

4.3.2 Simple Models between Acoustical Measures and Architectural Parameters

4.3.2.1 Linear models

4.3.2.1.1 Correlation coefficients analysis. Figure 4.2 presents each of the eight acoustical measures plotted with the architectural parameter with which it was most highly correlated (in some cases a nonlinear model will give a better fit as seen in the following subchapter). The variance of L values can be largely explained with just one of the fifteen architectural parameters ($R^2 \approx 0.77$). For RT, EDT, C80 and TS the percentage of variance explained by just one architectural parameter is not very significant (R^2 between 0.37 and 0.55). The bass ratios, with $R^2 \leq 0.25$ cannot be explained or predicted significantly with the use of just one architectural parameter. The equations for those linear models are presented in Table 4.4.

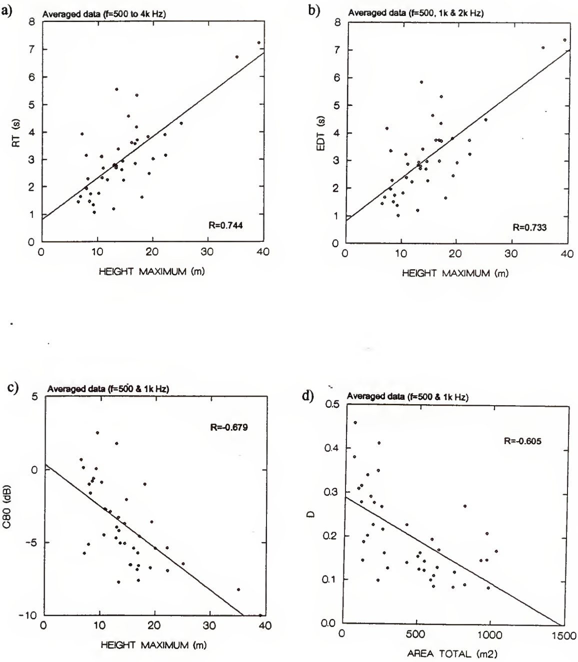


Figure 4.2 - Mean values of acoustical measures for each church (41 points = 41 churches) plotted vs. the architectural parameters with which it was highly correlated. The best linear model is shown for each case with the frequency averaging option used.
a) RT; b) EDT; c) C80; d) D; e) TS; f) L; g) BR_RT; h) BR_L.

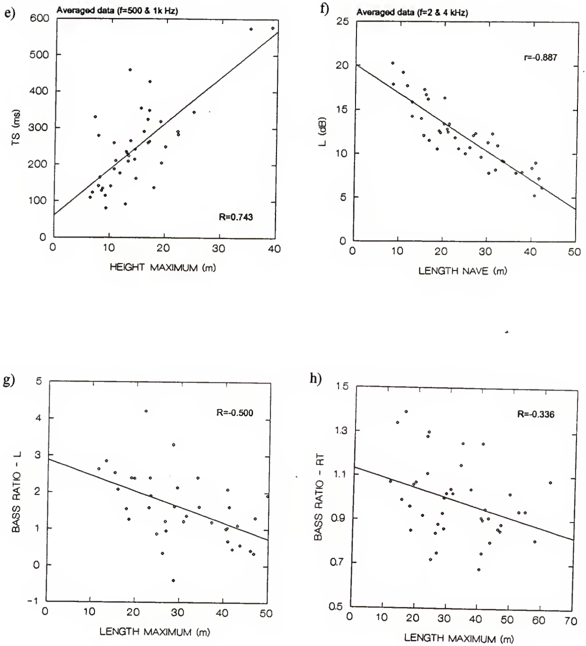


Figure 4.2 -- continued.

TABLE 4.4 - Relationships between acoustical measures and architectural parameters with linear models.

EQUATIONS (SIMPLE LINEAR MODELS)	ST Error of Estimate	R^2	OPTION
RT = 0.805 + 0.152 H_MAX RT = 0.785 + 0.176 H_MAX	0.9 s 1.1 s	0.55 0.54	41_4H 41_2F
EDT = 0.818 + 0.156 H_MAX EDT = 0.754 + 0.171 H_MAX	1.0 s 1.1 s	0.54 0.54	41_3F 41_2F
C80 = 0.365 - 0.287 H_MAX	2.2 dB	0.46	41_2F *
D = 0.289 - 0.00020 AREA_TOT	0.078	0.37	41_2F *
TS = 60.835 + 12.634 H_MAX	79 ms	0.55	41_2F
L = 20.064 - 0.327 L_NAVE L = 21.405 - 0.317 L_NAVE	1.7 dB 1.8 dB	0.79 0.75	41_O24 * 41_2F *
BR_RT = 1.104 - 1.640 ALPHA	0.16	0.14	all options *
BR_L = 2.663 - 0.047 L_NAVE	0.81	0.25	all options *

* Better fit available with nonlinear model (see Table 4.6)

4.3.2.1.2 Correlations controlled by architectural styles. A similar analysis was made using only the 500 & 1000 Hz frequency bands (option 41_2F) and controlling for each of the architectural styles. The results are shown in Table 4.5. There, it can be seen that higher values than the all church-average correlation coefficient, are present in the Gothic, Romanesque and Contemporary churches giving, to those samples, a greater uniformity than the ones from the Visigothic, Manueline to Neoclassic styles. This can be useful in the characterization of an identifiable acoustical characteristic to be attributed to buildings of those styles. Baroque and Manueline churches present a lower than the all church-average value due to the wide differences in the interiors and finishes of these churches.

4.3.2.2 Nonlinear models

Nonlinear regression models (logarithmic and quadratic smooth) were tested. The results generally agree with those presented above. In Figure 4.3 the cases in which a better than linear fit was found between an acoustical measure and an architectural parameter are

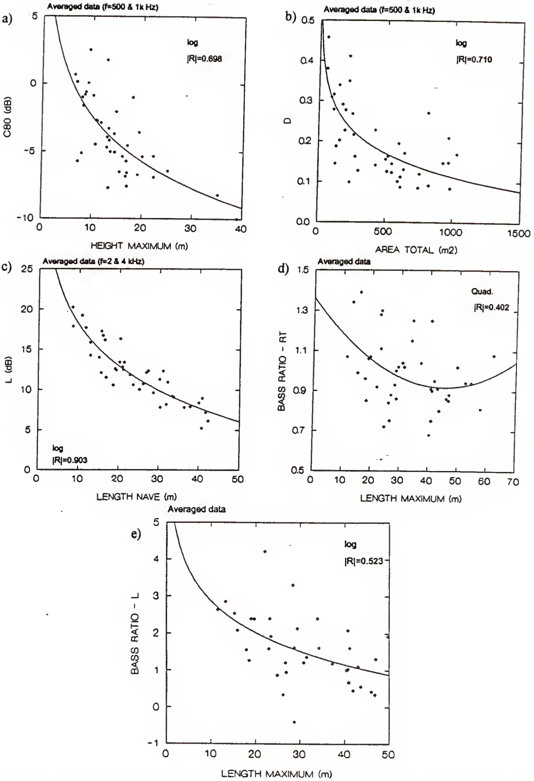


Figure 4.3 - Mean values of acoustical measures for each church (41 points = 41 churches) plotted vs. the architectural parameters with which it was highly correlated. The best nonlinear model is shown for each case with the frequency averaging option used.
a) C80; b) D; c) L; d) BR_RT; e) BR_L.

shown. Those are: C80, D, L, BR_RT and BR_L. However the differences in the R values between the linear and the nonlinear regression lines for each case are not significant (from 0.002 to 0.105 - $\Delta R_{average} = 0.05$). There is not a significant improvement in using nonlinear models (at least the logarithmic or quadratic smooth) in these cases. The equations for those five nonlinear models displayed in Figure 4.3 are presented in Table 4.6 (also with the corresponding equation for the 41_2F option for the L measure).

TABLE 4.5 - Pearson correlation coefficients (|R|) between acoustical measures and architectural parameters controlling for architectural style.

	ARCH. STYLE	RT	EDT	C80	D	TS	L	BR_RT	BR_L
-	ALL STYLES	0.744h	0.733h	0.679h	0.605at	0.742h	0.887ln	0.433α	0.500ln
1	*VISIGOTHIC*	N/A	-	-	-	-	-	-	-
2	*ROMANESQUE*	0.835h	0.821h	0.867hn	0.823hn	0.846v/a	0.898s	0.462w	0.546w
3	*GOTHIC*	0.954v	0.943v	0.984h	0.983h	0.952v	0.978lm	0.746lm	0.737α
4	*MANUELINE*	0.652α	0.663v	0.761α	0.797w	0.632α	0.927lm	0.680α	0.905v
5	*RENAISSANCE*	N/A	-	-	-	-	-	-	-
6	*BAROQUE*	0.584hn	0.553hn	0.684hn	0.732hn	0.570lm	0.863ln	0.322h	0.415ln
7	*NEOCLASSIC*	N/A	-	-	-	-	-	-	-
8	*CONTEMPORARY*	0.804at	0.776at	0/688at	0.85 at	0.726at	0.977at	0.769h	0.978w

Notes: an -Area nave; at - Area total; h - Height maximum; hn - Height nave; lm - Length maximum; ln - Length nave; s - Number of seats; v - Volume total; v/a - Volume total / Area total; w - Width nave; α - Alpha average; N/A - Not available (small sample to compute)

TABLE 4.6 - Relationships between acoustical measures and architectural parameters.

EQUATIONS (Simple nonlinear models)	OPTION	St. Error of Estimate	R^2
C80 $= 8.850 - 4.887 \log_n (H\_MAX)$	41_2F	2.1 dB	0.49
D $= 0.685 - 0.083 \log_n (AREA\_TOT)$	41_2F	0.068	0.50
L $= 35.238 - 7.456 \log_n (L\_NAVE)$	41_O24	1.6 dB	0.82
L $= 36.101 - 7.219 \log_n (L\_NAVE)$	41_2F	1.7 dB	0.78
BR_RT $= 1.358 - 0.019\, L\_MAX + 0.00021\, (L\_MAX)^2$	all options	0.16	0.16
BR_L $= 5.264 - 1.094 \log_n (L\_MAX)$	all options	0.79	0.25

4.3.3 General Linear Models between Acoustical Measures and Architectural Parameters

4.3.3.1 Forward versus backward stepwise modeling

With the goal of trying to find a better linear model that can explain the relationships between acoustical measures and architectural parameters, general linear models were calculated. The forward stepwise modeling method was chosen rather than the backward stepwise method because the objective was to improve the prediction of one acoustical measure from the previous use of just one architectural parameter. Several tests using both models gave very different results not only with regard to the multiple R^2 but also concerning the variables included in the subset models found. Each model should add just 1 or 2 architectural parameters as regressors in order to find a subset model that can better explain the variance of that particular acoustical measure. That is the operating procedure also of the forward stepwise method. The backward method starts with all the architectural parameters included and gradually removes term after term. In both cases an α-to-enter (or -to-remove) equal to 0.05 was chosen. The accuracy of the models was judged primarily by their R^2 which represents the percentage of variance explained and secondarily by the standard error of the estimate which represents the magnitude of differences between estimated and observed values).

4.3.3.2 Prediction equations

Using the average data in the 500 & 1000 Hz octave bands (option 41_2F), the calculated general linear models are presented in Table 4.7. Appendix O presents the standard errors and the standardized coefficients for the model's predictors.

The R^2 coefficients can be improved, that is, the percentage of variance explained can be greater if the expected values for some acoustical measures calculated by the diffuse field theory formulas (Chapter 3.6) are included in the models. In that case, knowing the real RT

which is usually easily measured in loco, better predictions for EDT, TS, C80 and L can be found. The same 0.05 was used for the α-to-enter or to-remove (see Table 4.8). If a larger α-to-enter/remove was chosen, it should be an $\alpha \geq 0.16$ in order to have all four of these general linear equations with at least one architectural parameter. But even then the R^2 would not improve except in the C80 model where a small increase of 0.03 would be found for its R^2.

These prediction equations and their defining coefficients were calculated using this 41 church sample. Therefore, the validity of their use must be thought with the sample from which it was originated (see Appendix K).

TABLE 4.7 - Relationships between acoustical measures and architectural parameters with general linear models.

GENERAL LINEAR MODELS	ST Error of Estimate	R^2
RT = 1.148 + 0.149 H_MAX + 0.078 W_NAVE - 13.383 ALPHA	0.91 dB	**0.71**
EDT = 1.075 + 0.145 H_MAX + 0.077 W_NAVE - 12.756 ALPHA	0.90 dB	**0.71**
C80 = 0.864 - 0.217 W_NAVE - 0.404 VTO_ATO + 35.121 ALPHA	1.2 dB	**0.85**
D = 0.452 + 0.000014 VOL_TOT - 0.007 L_NAVE - 0.008 W_NAVE - 0.014 VTO_ATO + 1.364 ALPHA	0.042	**0.84**
TS = 85.448 + 10.603 H_MAX + 5.941 W_NAVE - 983.36 ALPHA	61 ms	**0.74**
L = 22.918 - 0.306 L_NAVE - 24.520 ALPHA	1.5 dB	**0.82**
BR_RT = 1.279 + 0.00045 SEATS - 0.008 L_MAX - 1.867 ALPHA BR_L = 2.663 - 0.047 L_NAVE	0.14 0.80	0.35 0.25

TABLE 4.8 - Revised predictions for acoustical measures (using averaged data - option 41_2F).

GENERAL LINEAR MODEL EQUATIONS (Using expected values)	R^2 (variance explained)	Standard Error of Estimate (STD of residuals)
$EDT = -0.019 + 0.976\ EDT_{exp}$	0.996	0.11 s
$TS = 8.518 + 0.974\ TS_{exp}$	0.985	14 ms
$C80 = 0.0576 + 1.045\ C80_{exp} - 0.025\ L\_MAX$	0.944	0.70 dB
$L = -0.196 + 0.966\ L_{exp}$	0.957	0.76 dB

As seen, the percentage of variance explained by the use of the expected values of the acoustical measures is significantly better than with the models using only the architectural parameters. Note that only the C80 measure needs the inclusion of some architectural parameter in the general linear models. This can be partially explained by the slightly greater diffusiveness of churches than concert halls.

4.4 Summary

The effect of fifteen simple architectural parameters on these acoustical measures was investigated. Prediction equations were calculated to estimate mean acoustical measures. It was found that simple nonlinear models gave only a slightly better ($\Delta R^2 < 0.14$) prediction fit than the linear models in the majority (70%) of the cases studied. Among these, the logarithmic smooth presents a better fit in many cases (C80, D and L). This is due to the logarithmic mathematical characteristic of many of those measures by their definition. General linear models using only two to five architectural parameters were calculated to predict the six main acoustical measures with 71% (RT and EDT) to 85% (C80) of variance explained and relatively small standard error of the estimates. The bass ratios could not be reasonably well predicted with the use of this set of architectural parameters ($R^2 \leq 0.35$). The expected values for some acoustical measures estimated by the use of the classical diffuse field theory equations largely increased the fitness of the predictions models from $R^2 = 0.944$ (for C80) to $R^2 = 0.996$ (for EDT) when they are included in the models.

CHAPTER 5
CLASSICAL EQUATIONS FOR THE CALCULATION OF THE REVERBERATION TIME

5.1 Purpose

The reverberation time equations have been the most widely used prediction tools in acoustical design because they are simple to use and usually give reasonable results. The first and perhaps the most widely used reverberation time equation is the Sabine equation (Sabine 1992). In the following years several revised equations were proposed like the Eyring or the Millington equations (Eyring 1930; Millington 1932). The purpose of this Chapter is to test the use of the Sabine and Eyring equations in churches especially when recesses and coupled spaces are present.

5.2 Sabine and Eyring Equations

In this study two classical equations, the Sabine and the Eyring, for the prediction of RT were applied to the 41 churches measured.

SABINE EQUATION $RT = 0.16\ V / A$

EYRING EQUATION $RT = 0.16\ V / [A_{air} - S_T \log_n (1 - \alpha_{avg})]$

where: V - Volume (m^3); RT - Expected Reverberation Time (s);

A - Total Absorption (m^2); α_{avg} - Absorption Coefficient (avg. all surfaces);

A_{air} - Air Absorption (m^2); S_T - Surfaces Total Area (m^2).

The Appendix L presents the results for the application of the Sabine and Eyring equations to this sample of churches. The predicted results (Table L.1) for the RT are slightly better (near 13%) with the Eyring equation than with the Sabine equation but nevertheless, there are huge differences between measured and estimated RTs. The differences are due to

the presence, in some churches, of chapels and other deep spaces that act as coupled spaces (see Chapter 5.4).

5.3 Analysis between RT Real and RT Expected

The measured RT values (RT real) and the predicted values using the Sabine or Eyring equations are plotted in the Figure 5.1 jointly with linear regression models using the option 41_2F, that is, only freq. = 500 and 1000 Hz. The Pearson correlation coefficients are presented in Table 5.1.

TABLE 5.1 - Matrix of Pearson correlation coefficients.

	RT(real)
RT(SABINE_VOL.TOTAL)	0.722
RT(SABINE_VOL.NAVE)	0.746
RT(EYRING_VOL.TOTAL)	0.717
RT(EYRING_VOL.NAVE)	0.743

Figure 5.2 shows the graphical representation of the RT real versus the RT calculated with the Sabine equation using the Volume Total and the Volume of the Nave only, together with the linear regression models. The fit of the linear regression line is clearly not perfect, therefore a new approach was tested and presented in Figure 5.3. Those two plots display the RT(Sabine) and RT(Eyring), using the Volume Total, with two linear models: one for the RT_Real = RT_Expected and the other for the best linear fit regarding the points that are not close to the previous line. The equations of these trends are:

RT = 0.501 * RT(SABINE_VOL.TOT) $R^2 = 0.968$ (Figure 5.3a)

RT = 0.538 * RT(EYRING_VOL.TOT) $R^2 = 0.976$ (Figure 5.3b)

This approach seems to give a good approximation for the data. The justification for the use of one or the other lines is based upon whether or not there are deep recesses such as

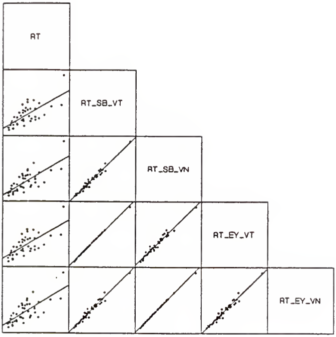


Figure 5.1 - Casement plot among measured and predicted RTs with linear regression models using freq.=500 & 1000 Hz (option 41_2F). SB-Sabine, EY-Eyring, VT-using volume total, VN-using volume of the nave.

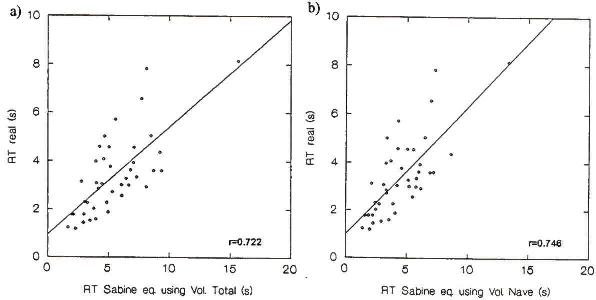


Figure 5.2 - Plots of measured (y axis) and predicted (x axis) RTs with linear regression models and Pearson correlation coefficients using the Sabine equation calculated with different volumes (41 points = 41 churches).
a) Using the total volume; b) Using the volume of the nave.

chapels or altars that act as coupled spaces present in the churches. All the churches close to the $RT_{real} = RT_{expected}$ are those without deep recesses. Therefore the prediction equation gives a good approximation of the results. The others are churches with chapels that act as coupled spaces artificially increasing the absorption of the room.

5.4 Coupled Spaces

The subdivision of the volume into a number of smaller volumes coupled together, results in very low RT without the addition of absorptive materials. Deep lateral chapels and even in certain cases, the main altar area (apse), can act as coupled spaces. This will entirely transform the analysis and application of the prediction equations.

The border between those coupled spaces and the main room acts as an absorptive surface with an indeterminate absorption coefficient α. Some authors have tried to determine values for the α of the recesses and coupled spaces in churches. Tzekakis using measurements in eight greek orthodox churches in Thessaloniki, found that the openings must have an α above 0.5. Shankland presents values between 0.38 and 0.67 using the results of measurements in four basilicas in Rome.

Cremer states that if the the equivalent absorption area of room 2 - the smaller room (A_{20}) is much smaller than the area of the opening between rooms (S_{12}), the two rooms can be treated as one. This approach was taken in the produced Table L.2. In other words, these rooms were not considered as coupled spaces because the interior absorption in the chapels or main altar is usually much smaller than the opening area because the walls, ceilings and part of the floors are made of stone. This approach did not produce satisfatory results.

Cremer also states, as a rule of thumb, that if the boundary area covered with absorptive materials in the coupled room (Sa) exceeds that of the coupling area to the main room (Sc), it should be treated as an open window ($\alpha = 1$); if not, the coupled room (room 2)

should be treated as part of the main room. Using that rule and considering that all chapels and the main altar area (apse) have at least a Sa = Sc due to the wood-carved altars that fill one of the walls entirely and freely supposing that the wood-carving is an absorptive material a new spreadsheet was calculated using an $\alpha = 0.9$ in all openings to chapels or to the main altar area (Appendix L.3). This approach did not produce satisfactory results. The answer seems to indicate the use of different α's for the main altar area (apse) and for the lateral chapels.

In many of the churches, the chapels can not be considered as coupled rooms due to their size or shape. As Kuttruff states, the necessity of considering coupling effects when calculating the RT arises if the area of the coupling aperture is substantially smaller than the total wall area of a partial room. Another explanation can be in the lack of diffusion that happens in some of the churches, especially those having very simple geometric shapes and extremely non-uniform distribution of absorption on their walls.

Neither the Sabine nor the Eyring equations provided a very good prediction of the measured RT. The use of the Total Volume or only the Nave Volume of each church in the RT calculation in one of those equations gave a Pearson correlation coefficient of approximately 0.73.

A different approach was then tested using two linear trends: one for the $RT_{real} = RT_{expected}$ and the other for the best fit regarding the points that were not close to the previous line. All the churches close to the $RT_{real} = RT_{expected}$ were those without deep recesses. The others were churches with coupled spaces that artificially increased the absorption of the room. Therefore the importance of the coupled spaces justified the search for a new approach in using the Sabine equation in these situations.

5.5 New Algorithm

5.5.1 Method

Lateral chapels, the main altar (apse) and lateral aisles, can in certain cases act as coupled spaces. This will entirely transform the analysis and application of the Sabine equation. A new algorithm for use in the Sabine equation considering the existence of coupled spaces was developed. An absorption coefficient for the opening of each coupled space (α_{CS}) was calculated depending on the geometric characteristics of the specific coupled space. With that α_{CS} a new Total Absorption for the church was calculated and the Sabine equation was used with the appropriate Final Volume. Volume Total was used if no coupled spaces and Volume Nave was used if chapels and main altar are coupled spaces, etc..

$$RT_{SABINE} = 0.16 \text{ V. Final} / A$$

where: V-Volume (m^3), α_{CS} -Absorption coefficient (coupled space),

A-Total absorption (m^2) = $\Sigma A_i + \Sigma \alpha_{CS\,j} S_j$, S-Coupled space opening surface area (m^2).

As Kuttruff states, the necessity of considering coupling effects when calculating the RT arises if the area of the coupling aperture is substantially smaller than the total wall area of the partial (or coupled) room. Using this idea, a geometrical parameter was found to weight the degree of coupling of a specific partial room to the main room volume. Using Figure 5.4 (where *l*, *w* and *h* are the length, width and height) by Kuttruff's rule, it is a coupled space if

$S_{12} < k \,.\, S_2$ where k = constant > 1 and $S_2 = \Sigma S_{2\,i}$ (3 walls in room 2 - the coupled room)

then $w \,.\, h < k\,(2 \,.\, l + w_2)\, h$

or $k > w / (2 \,.\, l + w_2) \approx 1 / [\,(2 \,.\, l/w) + 1\,]$, because $(w_2 / w) \approx 1$

or finally $l/w > (k - 1) / 2 \quad , k > 1$

If $k = 2, \; l/w > 0.5$

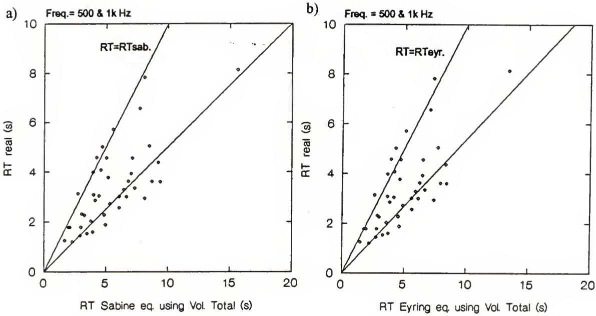


Figure 5.3 - Plots of measured (y axis) and predicted (x axis) RTs using the Sabine and the Eyring equations with two linear trends, one for the $RT_{REAL} = RT_{EXPECTED}$ and the other for the best linear fit regarding the points that are not close to the previous line.
a) Using the Sabine equation; b) Using the Eyring equation.

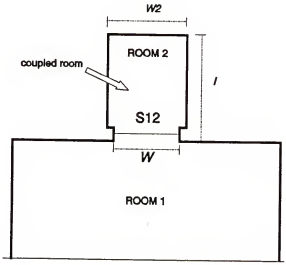


Figure 5.4 - Plan sketch of a general church with a coupled space (not to scale). l-length, S_{12}-opening surface area, w-opening width, $w2$-coupled space width, Room 1-main room, Room 2-coupled room.

......

k = 3, $l/w > 1.0$

......

Therefore, l/w appears as a good parameter to characterize a coupled space. Then, $\alpha_{CS} = f(l/w)$. This function *f* must be restricted to the limits of α_{CS}. That is, it must be between 0 and 1. The TANH (hyperbolic tangent) was chosen with an *x* axis shift to eliminate the presence of negative α_{CS}'s. Therefore, the final transfer function is:

$$\alpha_{CS} = \tanh [\ a\ (l/w - b\ )\ ]$$

TABLE 5.2 - Coefficients to use in new algorithm to account for the coupled spaces effect in the use of the RT Sabine equation.

Type of Coupled Space	a	b
CH - CHAPELS	0.007	0
MA - MAIN ALTAR (APSE)	0.985	0.6
LA - LATERAL AISLES	0.0118	-14

Table 5.2 presents the best parameters *a* and *b* that were found by experimentation, using the 41 church sample. Other general rules in the use of this algorithm are presented below.

CHAPELS are only considered as coupled spaces if $l/w > 0.6$. l/w is the average of all $(l/w)_{\text{chapel } i}$ weighted by their opening surfaces S_i. This is the area of the vertical plan that is the border between the chapel and the main volume of the church. The total interior absorption should be included. In the simplified version of this method, this absorption is sufficient in the account of the total absorption for this type of coupled space. If the chapels are *inside* the lateral aisles area, they should be omitted if that volume is also omitted as referred below if $l/w_{\text{(lateral aisles)}} > 0.70$.

MAIN ALTAR (APSE) is only considered as coupled spaces if $l/w > 0.6$. The total interior absorption should be accounted for (normally this is a very small quantity).

LATERAL AISLES are only considered as coupled spaces if $l/w > 0.4$. In this type of coupled space the parameters l and w are defined as seen in Figure 5.5 where l = width of lateral aisle and w = height of each opening. The volume of the Lateral Aisles is only excluded of the Total Volume of the church if $l/w > 0.70$:

Volume Final = Volume Nave - Volume Lateral Aisles if $l/w > 0.70$ or Volume Final = Volume Nave if $l/w \leq 0.70$. The total interior absorption should be included.

5.5.2 Results

The results of this algorithm applied to the 41 churches are presented in Appendix L.4 and summarized in Figure 5.6. An average of 16% between measured and predicted RT was found for the total 41 churches. This is a huge improvement from the 71% average absolute difference found without the use of this algorithm (see Appendix L.2).

Using *seconds*, the average of the absolute differences is 0.49 s in the RT expected, which can be considered a very good result due to the large values for the RTs involved. Figure 5.6 presents the plot of the RT_{REAL} vs RT_{SABINE}(w/ CS) and the prediction line. This prediction linear equation ($RT_{REAL} = -0.003 + 0.999\ RT_{SABINE}$) with R = 0.887 is very close to the ideal $RT_{REAL} = RT_{SABINE}$. The differences found between RT_{REAL} and RT_{SABINE} are slightly correlated with the height of the churches. The Pearson correlation coefficient between the ΔRT and the fifteen architectural parameters used are in Table 5.3.

Figure 5.7 shows the plot of the RT Differences (in second) versus the Maximum Height. The Maximum Height appeared as a justification for part of the differences found between RT_{REAL} and RT_{SABINE} in a general linear model to predict the RT_{REAL} with the use of

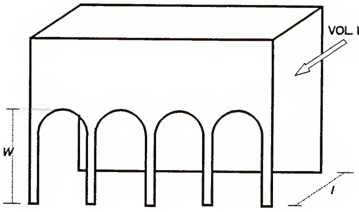


Figure 5.5 - 3-D sketch of lateral aisles in a general church (not to scale). *l*-width of lateral aisle, *w*-width of opening to lateral aisle, vol_{LA}-volume of lateral aisle.

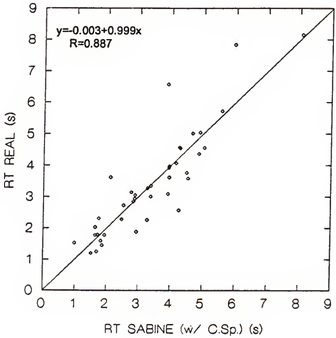


Figure 5.6 - Plot of measured (y axis) vs. predicted (x axis) RTs with linear prediction line and Pearson correlation coefficient.

TABLE 5.3 - Pearson correlation coefficients between ΔRT and the fifteen architectural parameters.

ARCHITECT. PARAMETERS	R	ARCHITECT. PARAMETERS	R
SEATS	-0.115	HEIGHT NAVE	-0.154
VOLUME TOTAL	-0.098	WIDTH NAVE	-0.181
VOLUME NAVE	-0.120	WIDTH AVERAGE	-0.134
AREA TOTAL	-0.102	V. TOTAL/AREA TOTAL	-0.086
AREA NAVE	-0.095	ALPHA AVERAGE	0.117
LENGTH MAXIMUM	-0.130	R_LOCAL	-0.014
LENGTH NAVE	-0.085	ABSORPTION TOTAL	-0.021
HEIGHT MAXIMUM	**-0.209**		

the RT_{SABINE} together with the fifteen architectural parameters. With an α-to-enter/remove = 0.15 the result was:

$$RT_{REAL} = -0.162 + 0.835\ RT_{SABINE} + 0.048\ \text{HEIGHT\_MAX} \quad (R^2 = 0.81)$$

This supports the explanation that the RT differences are due to the lack of diffusion that occurs in some of the churches, especially those having simple geometric shapes and extremely non-uniform distribution of absorption on their walls. This occurs in rectangular churches with smooth, reflecting walls and a tall ceiling. The absorption is mainly concentrated on the ceiling if it is wood or/and on the floor if it is wood or if wooden pews are used. In this case a two-dimensional reverberant sound field can be built.

Generally, the higher the ceiling, the longer the RT. The higher ceiling can almost act as a reverberant chamber included in the main room. This will only happen if the ceiling is non absorptive, that is, if it is not made of wood (in this sample of churches). To check this hypothesis the 41 churches were grouped according to their ceiling type (wood and non wood). The Pearson correlation coefficients were then calculated between these two groups and the ΔRT. The results are found in Table 5.4.

Figure 5.8 shows the RT differences grouped by the two groups of ceiling type with the standard error interval. An ANOVA test was calculated to determine if these two groups of ceiling types were statistically different. It was found that, at a level of probability (p-

value) higher than 0.12, the two groups were statistically different. Therefore it can be concluded that there are enough data to support the idea that a reverberant ceiling effect may play a role in the differences found between the RT real and the RT calculated by the Sabine equation. Therefore a new improvement in the proposed algorithm could be to consider that a reverberant ceiling effect be included in the total absorption parameter in the Sabine Equation or in the prediction value for the RT (as a ΔRT). This is another possible path for further research in this area.

TABLE 5.4 - Pearson correlation coefficients between ΔRT and Height maximum.

TYPE OF CEILING	NUMBER OF CHURCHES	R	
		ΔRT in seconds	ΔRT in percentage
WOOD	22	0.030	-0.004
NON WOOD	19	-0.216	-0.154

5.5.3 Frequency Average Options

The seven options of frequency band averaging to obtain a representative single number for each church parameter (see Chapter 3.4), were tested to compare the predicted RT by the use of the Sabine equation including the coupled spaces algorithm with the real RT measured. The Pearson correlation coefficients are displayed in Table 5.5.

TABLE 5.5 - Pearson correlation coefficients for RT(Sabine) vs. seven options of frequency averaging methods.

	RT (SABINE)
RT (REAL) Freq.= 125-1k Hz	0.870
RT (REAL) Freq.= 2 & 4 kHz	0.875
RT (REAL) All Frequencies	0.879
RT (REAL) Freq.= 250-2k Hz	0.884
RT (REAL) Freq.= 500-2k Hz	0.887
RT (REAL) Freq.= 500 & 1k Hz	0.887
RT (REAL) Freq.= 500-4k Hz	0.888

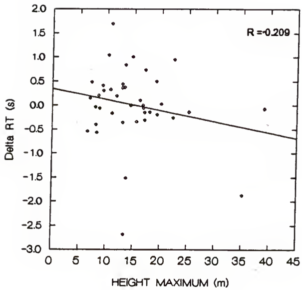


Figure 5.7 - Plot of the RT differences (Delta RT = RT_{REAL} - RT_{SABINE}) vs. Maximum Height of each church with linear regression line and correlation coefficient (41 points = 41 churches).

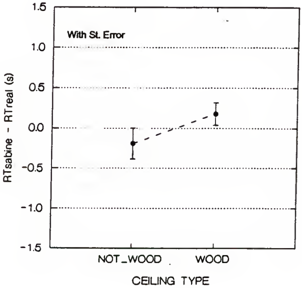


Figure 5.8 - Analysis of the effect of ceiling type (*wood* and *non wood*) differences (RT_{REAL} - RT_{SABINE}). Mean values for all the churches in each ceiling type are shown with one standard error confidence interval.

Again, the chosen method of using only the 500 and 1000 Hz octave bands in the averaging process appears as the best (or almost the best ...). However the differences among the options ($\Delta R < 0.02$) are not significant.

5.5.4 Simplified Method

A simplified method of the new algorithm presented in 5.5.1 is now described. The α_{CS} of the CHAPELS should be equal to 0. The interior absorption of each chapel is normally sufficient to consider the effect of chapels in the overall absorption of the church. Therefore an $\alpha_{CS\,(CHAPELS)} = 0$ can be used as a simplification. The α_{CS} of the LATERAL AISLES should be equal to 0.17. The Lateral Aisles (LA) have very similar proportions relatively to the church main volume. Therefore an $\alpha_{CS\,(LATERAL\ AISLES)} = 0.17$ can be used as a simplification if $l/w > 0.4$. Then the apse or Main Altar area (MA) will be the only coupled space to be considered if $l/w > 0.60$ in this simplified version of the algorithm presented.

$$A_{CS} = \alpha_{CS\,(CH)} \cdot S_{CH} + \alpha_{CS\,(LA)} \cdot S_{LA} + \alpha_{CS\,(MA)} \cdot S_{MA}$$

$$A_{CS} = 0 \cdot S_{CH} + 0.17 \cdot S_{LA} + \tanh\left[\,0.985\,(\,l/w - 0.6\,)\right]$$

5.6 Summary

The use of the Sabine and Eyring reverberation time equations was tested to estimate the measured reverberation times in this sample of churches. The Eyring equation gives slightly better results than the Sabine equation in predicting the RT when the effect of coupled spaces is not considered. Two trends were clearly distinguishable in the RT values indicating a need for the analysis of the coupled spaces in the prediction of RT in churches that could better explain that difference between measured and predicted RTs. The effect of coupled spaces was analyzed and a new algorithm for the application of the Sabine equation in churches was developed producing an average of 16% in the differences between the reals and predicted RTs compared to a 71% difference using the standard Sabine equation. Coupled

spaces (CS) were found to act as windows with a characteristic α depending on their dimensions. The recesses in churches were grouped in three types: main altar area (apse), chapels and lateral aisles. Each type of coupled space has a particular acoustical behavior with different a and b parameters in the calculated equation. There are two major reasons that three types of coupled spaces are needed. The first reason is the relative position of the sound source to the coupled space, that is, concerning the direction from which the sound enters the coupled space. Second is the volume of the coupled space relative to the volume of the main room. It was found that those recesses only acted as coupled spaces if their length / opening_width > 0.6 or if the aisle_width / opening_height > 0.4 in lateral aisles. The remaining differences found between the measured RTs and the predicted RTs with this new algorithm were hypothesized to be related to what was called a reverberant ceiling effect which is presumed to be due to a two-dimensional reverberant sound field that builds up near a very tall ceiling in churches.

CHAPTER 6
THE USE OF RASTI IN CHURCHES

6.1 Purpose

Praying and lecturing, that is, activities mainly related to speech, are an important part of services in Catholic churches. Nevertheless, acoustical problems in the intelligibility of speech are the general rule in this type of building. They are not as important as in other types of rooms where speech is used perhaps because the experience of the mass and related services and its liturgical structure is crucial to our ability to recognize speech. The purpose of this Chapter is to study speech intelligibility in churches by the use of the RASTI and to analyze its relationships with other acoustical measures and architectural parameters.

6.2 Speech and RASTI

There is not a large amount of information on the use of the RASTI (Rapid Speech Transmission Index) as a tool to predict speech intelligibility in churches or other similar religious buildings. Very few studies in this area have been published (Hammad 1990; Abdelezeez et al. 1991; Anderson and Jacobsen 1985). The study of the relationships between RASTI and other acoustical measures appears as an interesting necessity. Therefore, several monaural acoustical measures pertinent to churches were evaluated and their relationships with RASTI calculated. Other studies were done regarding the effect of the sound source location, the effect of architectural styles, etc., on RASTI values measured in churches.

Speech intelligibility was estimated by the calculation of the RASTI which may be related to subjective intelligibility (Brüel & Kjær 1986). The RASTI method, a simplified version of the STI (Speech Transmission Index), was developed in 1984 by Houtgast and

Steeneken. The advantage of RASTI regarding other objective and subjective methods is that it can be quickly evaluated without speakers or listeners. It involves the measurement of the reduction of a transmitted test signal that has certain characteristics such as intensity, modulations or directional proprieties, representative of the human voice. A transmitter generates pink noise at levels of 59 and 50 dB , or +10 dB, for the 500 and 2000 Hz octave bands, respectively, to mimic the long-term speech spectrum and with similar directional proprieties that would be measured from a human speaker (at 1 m). The low frequency modulations that exist in speech are simulated by nine discrete modulation frequencies between 0.7 to 11.2 Hz. A microphone receives the signal that is analyzed by the receiver unit to calculate the RASTI from the modulation reduction factors. Perfect transmission of speech requires that the received temporal speech envelope replicates the one emitted. This can be quantified in terms of alterations brought in the modulation of the speech envelope as the result of the acoustical characteristics of the room. RASTI is an index between 0 and 1 derived from the measured reduction in signal modulation between the transmitter and receiver positions. RASTI automatically includes the effect of reverberation and background noise because it is derived from the measured signal degradation. RASTI values can be transformed to a speech intelligibility scale as seen in Table 6.1.

TABLE 6.1 - Definition of the RASTI transfer function.

RASTI (%)	SUBJECTIVE INTELLIGIBILITY SCALE
0 - 30	*BAD*
30 - 45	*POOR*
45 - 60	*FAIR*
60 - 75	*GOOD*
75 - 100	*EXCELLENT*

(Source: Brüel & Kjær 1986)

TABLE 6.2 - RASTI statistics from the 41 church sample.

PARAMETER	RASTI (%)
Minimum	21
Maximum	79
Mean	43
Median	40
St. deviation	12

In each church the transmitter location was in front of the main altar at 1.65 m above the floor to represent a standard speech situation during services. Eight positions on average

in each church were used for the receiver location. In each receiver position three or four measurements were taken and then averaged to give the RASTI value at that location. In total, nearly 1200 data-points were collected. Table 6.2 presents a simple general statistical analysis concerning all data collected.

Figures 6.1 to 6.3 present general analyses of the RASTI data collected. Figure 6.1 displays the histogram of all the RASTI data measured (nearly 350 points). Figure 6.2 shows the mean RASTI value in each church and their confidence interval with one standard deviation. The mean values range from 0.33 to 0.62 where the subjective quality is judged Fair or Poor. Only two churches have mean RASTI values above 0.60. The vast majority of churches have RASTI values below 0.45 giving a poor rating in the quality of speech intelligibility.

Figure 6.3 plots the variation of RASTI with the distance to the sound source with a logarithmic smoothing. In this case, only the positions on the longitudinal axis of each church were used. There is a steep decrease in the positions closer to the sound source where positions are located in the direct field and a reduced slope at larger distances where positions are located in the reverberant field.

6.3 RASTI and the Acoustical Measures

Statistical analysis was used to determine the relationships between the eight acoustical measures and the RASTI. Data were used only from those positions in which all the acoustical measures were determined (nearly 150 points). Models were calculated using several types of smoothing to determine the best regression line for the correspondence between RASTI and each of the other acoustical measures. The models tested were the linear

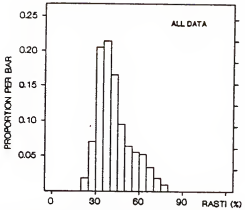


Figure 6.1 - Histogram of RASTI data collected in the 41 church sample.

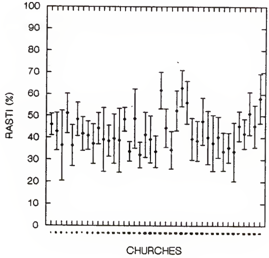


Figure 6.2 - Mean values of RASTI with one standard deviation confidence interval for each church (numbered 1 to 41 from left to right on the x axis).

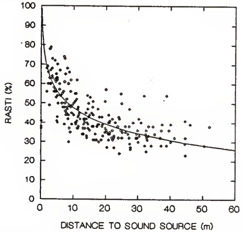


Figure 6.3 - RASTI values vs. receiver distance to sound source in all churches with logarithmic smooth.

($y=a+b.x$) and some nonlinear: logarithmic ($y=a+b.log_n x$), power ($y=a.x^b$) and exponential ($y=a+b.e^{c.x}$). Two approaches were followed: Using all data including points in the transmitter's direct field and using data without the direct field values. That is, excluding the points located at a distance < 5 m from the transmitter or not in the main volume of the church, like in chapels or in the main altar area.

For each of the eight acoustical measures and for each octave frequency band (38 cases in all) linear and nonlinear models were tested. Table 6.3 summarizes the results found displaying the type of smoothing used, the R^2 for each model and the corresponding equations for the best model for each acoustical measure. Figure 6.4 shows the plots for the models.

To find a better linear model to predict RASTI in any position within a church not in the direct field of the sound source using the other acoustical measures, a general linear model was calculated using the forward stepwise modeling method (with an α-to-enter/remove = 0.05), having a R^2 = 0.835:

RASTI = - 6.139 EDT(4k) + 1.479 C80(2k) + 12.417 D(125) + 0.046 TS(4k) + 0.692 BR_L .

As presented above, statistical models were calculated to quantify relationships between RASTI values and eight other acoustical measures. It was found that RASTI values within churches in positions not in the direct field of the sound source can be reasonably predicted by the use of the TS(1 kHz) in the same position, with a R^2 = 0.80. Regardless of the receiver position within the church, RASTI can be predicted (with a R^2 = 0.74) by the use of the C80(2 kHz). If the assumption that RASTI is a good predictor of speech intelligibility is valid (Brüel & Kjær 1986), then TS(1kHz) will also be one. Regardless of the receiver position within a church, RASTI was found to be easily predicted with the use of C80(2 kHz). Some of the 38 acoustical measures (considering each of the frequency bands) tested can be used together in a general linear model to explain 84% of the variance of the RASTI.

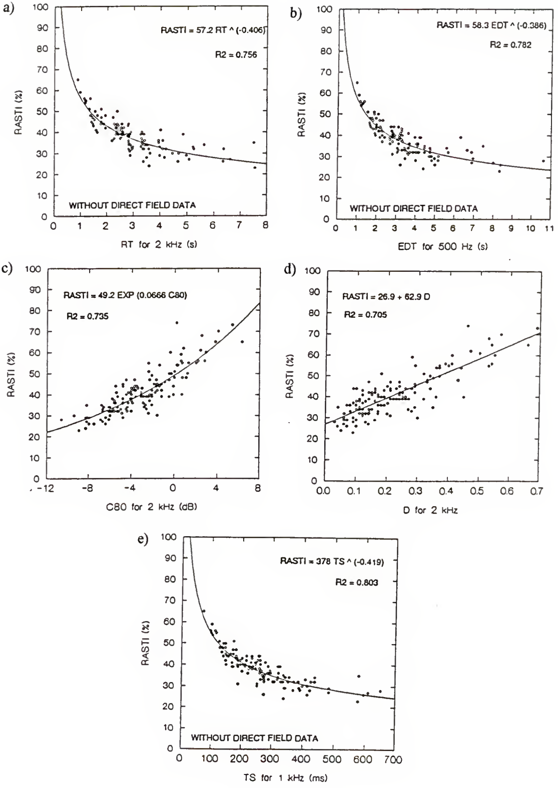


Figure 6.4 - Relationships among values of RASTI and the acoustical measure with different smoothing (power, exponential and linear). Prediction equations with squared correlation coefficients are shown.
a) RT_2k; b) EDT_500; c) C80_2k; d) D_2k; e) TS_1k.

Concerning the two approaches for this study (data with or without the direct field positions) it was found that the exclusion of the direct field data strongly affected only the prediction models for RT and EDT (achieving a 55% higher R^2), because RT and EDT are generally relatively constant within a church and are not strongly affected by the proximity of the sound source. Loudness (L) does not appear as an important characteristic regarding the RASTI values ($R^2_{maximum} = 0.167$) because the intelligibility of speech under reverberant conditions depends usually on the direct sound being at greater intensity than the reverberant sound.

TABLE 6.3 - Models between RASTI and the acoustical measures.

Acoustical Measure	Direct Field Data	Type of Smoothing	R^2	Equation	Fig.
RT(125)	No	Power	0.629		
RT(250)	No	Power	0.679		
RT(500)	No	Power	0.731		
RT(1k)	No	Power	0.743		
RT(2k)	No	Power	**0.756**	57.149 (RT2k) ^ (-0.406)	6.4a
RT(4k)	No	Power	0.753		
EDT(125)	No	Power	0.627		
EDT(250)	No	Power	0.690		
EDT(500)	No	Power	**0.782**	58.335 (EDT500) ^ (-0.386)	6.4b
EDT(1k)	No	Power	0.775		
EDT(2k)	No	Power	0.779		
EDT(4k)	No	Power	0.771		
C80(125)	Yes	Linear	0.516		
C80(250)	Yes	Exponential	0.534		
C80(500)	Yes	Exponential	0.667		
C80(1k)	Yes	Exponential	0.655		
C80(2k)	Yes	Exponential	**0.735**	49.19 EXP [0.06659 C80(2k)]	6.4c
C80(4k)	Yes	Linear	0.677		
D(125)	Yes	Linear	0.497		
D(250)	Yes	Linear	0.509		
D(500)	Yes	Linear	0.700		
D(1k)	Yes	Linear	0.680		
D(2k)	Yes	Linear	**0.705**	26.91 + 62.92 D(2k)	6.4d
D(4k)	Yes	Linear	0.621		
TS(125)	No	Power	0.645		
TS(250)	No	Power	0.675		
TS(500)	No	Power	0.784		
TS(1k)	No	Power	**0.803**	378.136 TS(1k) ^ (- 0.419)	6.4e
TS(2k)	No	Power	0.787		
TS(4k)	No	Power	0.736		
L(125)	Yes	Linear	0.141		
L(250)	Yes	Linear	0.120		
L(500)	Yes	Linear	0.122		
L(1k)	Yes	Linear	0.108		
L(2k)	Yes	Exponential	0.128		
L(4k)	Yes	Exponential	**0.167**	30.45 EXP [0.02594 L(4k)]	
BR_RT	No	Linear	0.033	46.28 - 8.274 BR_RT	
BR_L	Yes	Linear	0.020	39.28 + 1.382 BR_L	

6.4 RASTI and Architectural Parameters

6.4.1 Single Number Average

With the fifteen architectural parameters described earlier used in this study, there is a need for a corresponding single RASTI value, representative of each church. Three options were tested as described in Table 6.4.

TABLE 6.4 - Three options to calculate averaged RASTI.

CODE	DEFINITION
RASTI_001	Using only 1 point in each church (the one in the middle of the longitudinal axis)
RASTI_AVG	Average of all positions in each church
RASTI_NDF	Average of all positions Not in the Direct Field of the sound source (excluding positions < 5 m from sound source or not in the main volume of the church)

6.4.2 Linear Models

Linear models were tested between each of the fifteen architectural parameters and the three options of determining a single RASTI value for each church. The results of the Pearson correlation coefficient found are displayed in Table 6.5. The highest correlation values were found using RASTI_NDF, that is, average without the positions in the direct field of the sound source. The reason for this is finding that, near the sound source (in a small area of the church), the RASTI values increase significantly, therefore greatly changing the total average. Also those positions are not representative of the real speech intelligibility because few or none of the people attending services sit so close to the sound source (the priest).

The highest |R| found was 0.558 between RASTI_NDF and the Area Total. However this only explains 31% of the existent variance ($R^2 = 0.311$). Other models were then sought.

6.4.3 Nonlinear Models

Nonlinear models were tested between each of the fifteen architectural parameters and the three options to determine a single RASTI value in each church. The models used were

the logarithmic ($y=a+b.log_n x$), power ($y=a.x^b$) and exponential ($y=a+b.e^{c.x}$). The results of the squared R coefficients found are presented in Table 6.6. The highest squared R ($R^2 = 0.456$) was determined to be between RASTI_NDF and the Volume of the Nave. Figure 6.5 shows the plot of that relationship where it can be seen that only in small churches (Volume < 3000 m^3) the average RASTI is significantly different from 0.35.

TABLE 6.5 - Pearson correlation coefficients (architectural parameters vs. averaged RASTI).

ARCHITECTURAL PARAMETER	RASTI_001	RASTI_AVG	RASTI_NDF
SEATS	-0.362	-0.457	-0.459
VOLUME TOTAL	-0.481	-0.492	-0.522
VOLUME NAVE	-0.486	-0.496	-0.528
AREA TOTAL	-0.493	-0.552	**-0.558**
AREA NAVE	-0.474	-0.546	-0.550
LENGTH MAXIMUM	-0.487	-0.497	-0.515
LENGTH NAVE	-0.479	-0.506	-0.522
HEIGHT MAXIMUM	-0.474	-0.462	-0.509
HEIGHT NAVE	-0.511	-0.438	-0.490
HEIGHT AVERAGE (Volume Total / Area Total)	-0.492	-0.432	-0.486
WIDTH NAVE	-0.440	-0.530	-0.512
WIDTH AVERAGE	-0.439	-0.541	-0.526
ALPHA AVERAGE	0.422	0.458	0.469
R LOCAL [A/(1-α_avg)]	-0.017	-0.039	-0.030
ABSORPTION TOTAL	-0.076	-0.098	-0.093

TABLE 6.6 - Squared correlation coefficients for architectural parameters vs. averaged RASTI.

ARCHITECTURAL PARAMETER	RASTI 001		RASTI AVG		RASTI NDF	
	R^2	Model	R^2	Model	R^2	Model
SEATS	0.131	LI	0.209	PW	0.215	EX
VOLUME TOTAL	0.376	LG	0.408	LG	0.443	PW
VOLUME NAVE	**0.389**	LG	0.419	PW	**0.456**	PW
AREA TOTAL	0.347	LG	**0.422**	LG	0.430	PW
AREA NAVE	0.341	LG	0.418	LG	0.425	PW
LENGTH MAXIMUM	0.267	LG	0.285	LG	0.303	LG
LENGTH NAVE	0.291	LG	0.328	LG	0.342	LG
HEIGHT MAXIMUM	0.262	PW	0.256	PW	0.315	PW
HEIGHT NAVE	0.276	EX	0.204	PW	0.267	EX
HEIGHT AVG (Vol.Total/Area Total)	0.266	PW	0.209	PW	0.271	PW
WIDTH NAVE	0.305	LG	0.392	PW	0.379	PW
WIDTH AVERAGE	0.283	LG	0.384	PW	0.377	PW
ALPHA AVERAGE	0.178	LI	0.209	PW	0.220	LI
R LOCAL [= A / (1 - α_{avg})]	0.107	PW	0.122	LI	0.135	PW
ABSORPTION TOTAL	0.126	LG	0.143	PW	0.158	PW

Notes: EX-exponential, LG-logarithmic, LI-linear, PW-power

6.4.4 General Linear Models

To increase the fitness of the models under study, general linear models were tested, between RASTI_NDF and the fifteen architectural parameters. The best model using only two architectural parameters was determined to be with the width of the nave (WIDTH NAVE) and the average absorption coefficient (ALPHA AVERAGE) ($R^2 = 0.540$). Figure 6.6 presents the plot of this general linear model. There, it can be seen that RASTI increases with the decreasing width of the nave or with increasing the α average of the church.

The best model using three architectural parameters was found to be with WIDTH NAVE the ALPHA AVERAGE and the HEIGHT NAVE ($R^2 = 0.726$). This general linear model was determined with the forward stepwise procedure (α-to-enter/remove = 0.05). Therefore 73% of the inter-church variance of the averaged RASTI is explained by the average absorption of the church and the width and height of the nave area, using the following model (standard error of the estimate = 0.04).

RASTI_NDF = 0.485 + 1.07 ALPHA_AVERAGE - 10^{-2} (0.703 HEIGHT NAVE - 0.594 WIDTH_NAVE)

In summary, the best models to predict an average value of RASTI in churches are presented in Table 6.7.

TABLE 6.7 - Summary of best models to predict an average RASTI in churches.

MODEL	R^2	ARCHITECTURAL PARAMETERS
BEST LINEAR	0.31	AREA TOTAL
BEST NONLINEAR (power)	0.46	VOLUME NAVE
BEST LINEAR w/ 2 arch. param.	0.54	ALPHA AVG. + WIDTH NAVE
BEST LINEAR w/ 3 arch. param.	0.73	ALPHA AVG. + WIDTH NAVE + HEIGHT NAVE

6.5 RASTI and Architectural Styles

Figures 6.7 and 6.8 present the analyses of the RASTI behavior controlling for the

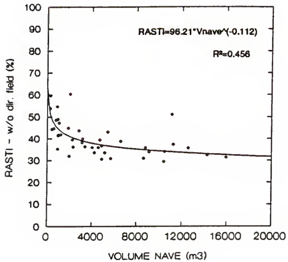


Figure 6.5 - Plot of the RASTI values without the direct field positions vs. the volume of the nave (the best predictor within the 15 architectural parameters). Prediction equation with power smoothing and squared correlation coefficient are shown.

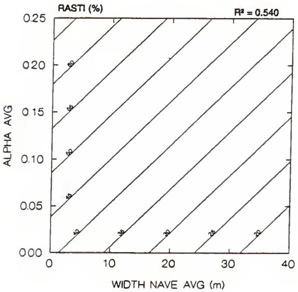


Figure 6.6 - Plot of the best general linear model to predict RASTI with two architectural parameters (average width of the nave and the average absorption coefficient) with squared correlation coefficient are shown.

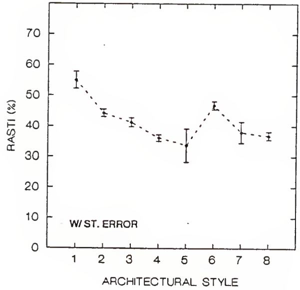


Figure 6.7 - Average RASTI data with one standard error confidence intervals plotted vs. the architectural styles in chronological order from left to right (1-Visigothic, 2-Romanesque, 3-Gothic, 4-Manueline, 5-Renaissance, 6-Baroque, 7-Neoclassic, 8-Contemporary).

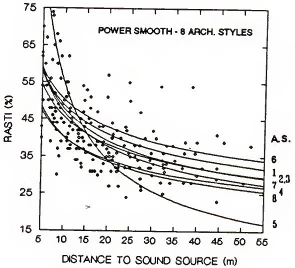


Figure 6.8 - RASTI plotted vs. receiver distance to sound source (altar) excluding the direct field positions with power smooth regression models for each architectural style (1-Visigothic, 2-Romanesque, 3-Gothic, 4-Manueline, 5-Renaissance, 6-Baroque, 7-Neoclassic, 8-Contemporary).

eight architectural styles as in Table 2.2. In Figure 6.7, mean RASTI values decrease until style *5* (Renaissance) and then sharply increase in style *6* (Baroque) to again decrease until style *8* (Contemporary). The break point in time where the general trend of the data changes is the period of the Protestant and Catholic Reformations where speech in Catholic churches became more important than it had been previously. Style *6* (Baroque) radically changed the acoustical behavior of the churches tested. Those changes seem to be soon forgotten. Again as with other acoustical measures (C80 and D) with the Neoclassic the previous trend of decreasing RASTI reappears perhaps due to the wave of antimodernism rules in the Church. That trend was leveled only in this century, where speech is perhaps the most important part of the religious services.

Figure 6.8 displays the RASTI variation with the distance to the sound source, near the Altar (excluding the direct field, distance < 5 m), with the regression lines for each architectural style. The Renaissance appears as the style with the lowest RASTI values and the Visigothic and Baroque as the ones with the highest RASTI values.

6.6 Pulpit Effect

Pulpits are now common in churches and other temples. The earliest documentary reference to a pulpit occurs in the 12th century (Briggs 1946), however they were uncommon in churches until the 15th century. After the 15th century they become increasingly common. Rules appeared in the related literature about their position and height within the church. Briggs and others like Mills, Sovik, Allen, Knudsen and Harris present some basic advice about the size and height of the pulpits. Others like Egan even have drawings showing preferred acoustical design techniques for pulpits.

The improvement in speech intelligibility provided by pulpits was tested in two churches: Church 12 (*Golegã*, 15th century) and Church 21 (*Sant. Sacramento*-Porto, 20th

century). Figure 6.9 displays the variation in the RASTI values with distance from the main altar using the sound source in the pulpit and in the altar. In both churches tested a higher RASTI was found for specific positions between 10 and 30 m from the altar when the sound source was in the pulpit. For longer distances, no improvement was determined and for shorter distances, a decrease in RASTI was found because those locations were behind the sound source usually in the apse or main altar area. Looking to these two Figures it seems that the use of a pulpit increases speech intelligibility. However, the improvement in the RASTI values was caused by the shorter distance between the sound source and each receiver due to the method used to measure distance. With the sound source in the pulpit, the distance to each receiver was smaller and therefore the RASTI was higher. This is supported by Figure 6.10. In this Figure the x axis represents the distance from the sound source not the distance to the main altar as in the previous Figure. That is, the distance to the altar or to the pulpit depending upon which position the sound source was emitting. In this analysis, there was no improvement in measured RASTI at a given distance when a pulpit was used. In fact, a small decrease in the RASTI values for the Pulpit positions was found.

Therefore it can be stated that the use of pulpits that do not have large canopies above them, as in these two cases, only improves the speech intelligibility due to the diminution of the distance between the receiver and the source. Pulpits were found not to be a direct acoustical resource but only an indirect way to increase the intelligibility of speech by decreasing the distance from the speaker to the listener.

These results were found using unoccupied churches. If occupied churches were used perhaps the effect of the absorption of the persons in the path of the direct sound from the altar would change the results. In this case, the use of an elevated pulpit and the emission of sound power over the congregation area could improve the speech intelligibility. In that

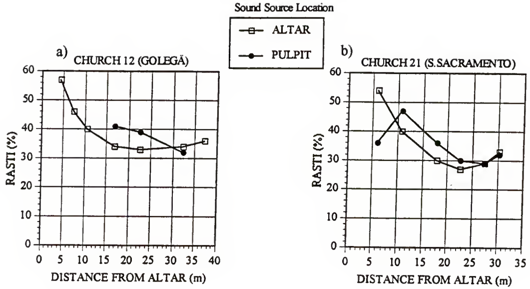


Figure 6.9 - RASTI values vs. receiver distance from altar with the sound source in the altar or on the pulpit.
a) Church 12 - *Golegã* -15th century; b) Church 21 - *S. Sacramento*, Porto - 20th century.

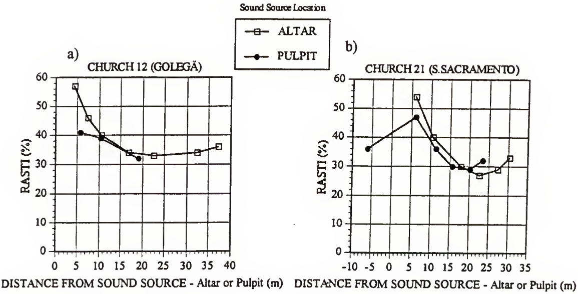


Figure 6.10 - RASTI values vs. receiver distance from sound source (Altar or Pulpit) with the sound source in the altar or on the pulpit.
a) Church 12 - *Golegã* -15th century; b) Church 21 - *S. Sacramento*, Porto - 20th century.

situation, when the sound source was in the Altar position, the RASTI values would be perhaps smaller than in the unoccupied church, due to the effect of the absorption of the persons seated in the previous rows, in the path of sound. Therefore, the effect of the pulpit could be different than the one tested.

6.7 RASTI versus Useful-to-Detrimental Sound Ratio

The importance of signal/noise ratio in speech intelligibility measures has been studied in the literature (Bradley 1986a,b). In order to compare this data to Bradley's work the following study was done. A useful-to-detrimental sound ratio (U80) was calculated from the corresponding early-to-late ratio (C80) and the ratio of background noise to speech energies (rasti speech energies). Due to the frequency characteristics of the RASTI transmitter, only the 500 and 2000 Hz octave-bands were used. The determination of the BL (background levels) was done by reading the frequency analyzer spectra taken in each church during the field-trip measurements.

The useful early energy is: $[C80 / (C80 + 1)] . E_{SL}$

The detrimental energy is: $[1 / (C80 + 1)] . E_{SL} + E_{BL}$

Where: E - Energy, B - Background, L - Level and S - Speech.

$$E_{BL} = 10^{BL/10} \quad \text{and} \quad E_{SL} = 10^{SL/10} \quad \text{then } (E_{BL} / E_{SL}) = 10^{(BL - SL)/10}$$

Then, the expression for a useful-to-detrimental ratio is obtained:

$$U80 = C80 / [1 + (C80 + 1). (E_{BL} / E_{SL})]$$

The calculation of SL (rasti speech levels) was done using the following expression:

$$SL = L_W + 10 \log_{10} [Q / (4\pi r^2) + 4 / R]$$

Where (calc. from Brüel & Kjær 1986): Q - Directivity factor = 1.3 or 1.6 (for 0.5 or 2 kHz)

$$R = A / (1 - \alpha_{avg})$$

r - distance to sound source (m)

L_W - Sound Power Level = 79 or 69 dB (for 500 or 2000 Hz)

Figure 6.11 presents the SL and BL (speech and background levels) for the two octave bands used. As seen in this Figure, the RASTI SPL was generally more than 15 dB above the background levels. This was due not to the power of the sound source that simulates the power of a human voice, but to the low levels of background noise found in the churches. The majority of the measurements were made at night when it was very quiet outside or during the day in quiet rural areas. The buildings have very thick doors and walls that reduce outdoor sounds substantially. For that reason, the U80 values were very similar (R = 0.994 / 0.996 for 500 / 2000 Hz) to the C80 values in the same positions (see Figure 6.12).

Figure 6.13 plots the results of the RASTI scores versus the U80 (2 kHz) values. The line shown on the Figure is the result of fitting a third-order polynomial to the data (with R^2 = 0.739). This model was done to directly compare to Bradley's studies where third-order polynomials were used. However, the use of a third-order polynomial does not bring a new insights to the problem nor is there a reasonable explanation for its use. Therefore a simpler model should be used, like an exponential (with which R^2 = 0.738 was found). Also a third-order polynomial will give two concavities in the general behavior of the line, not in agreement with the physics of the subject under study. Nevertheless, this Figure 6.13 shows that RASTI values are closely related to U80 (2 kHz) values.

Appendix M presents the results for the squared correlation coefficients for the relations between RASTI and C80, U80, RT or EDT as a comparison between Bradley's work using 5 or 10 rooms and this study presented here. It must be clear that Bradley did not use the RASTI but Speech Intelligibility Scores using a Fairbanks rhyme test. Therefore the smaller R^2 that he found are reasonable due to the nature of his studies.

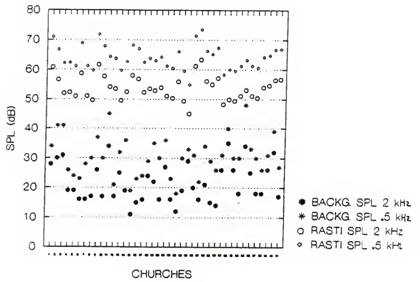


Figure 6.11 - Sound pressure levels (SPL) for the 41 churches (numbered 1 to 41 from left to right on the x axis) regarding the background noise (BACKG.) and the RASTI for the 2 frequency bands used (500 Hz and 2000 Hz).

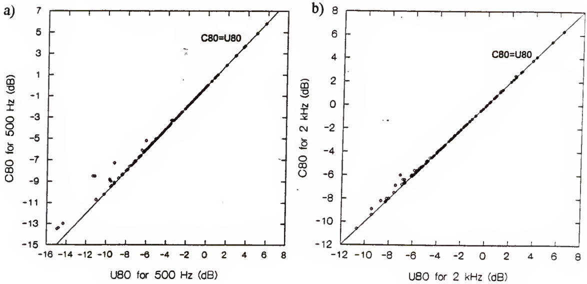


Figure 6.12 - Plots of U80 vs. C80 with linear regression lines.
a) 500 Hz data; b) 2000 Hz data.

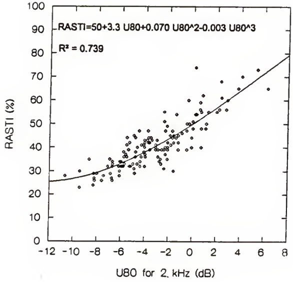


Figure 6.13 - Plot of RASTI vs. U80 values with best fit of third-order polynomial. Equation and squared correlation coefficient are shown.

6.8 Summary

The use of RASTI in churches was studied and the relationships with acoustical and architectural parameters identified. The vast majority of churches have RASTI values below 0.45 (0.40 was the calculated median) giving a poor rating in the quality of speech intelligibility.

RASTI values within churches, in positions not in the direct field of the sound source, can be predicted by the use of TS at 1000 Hz (TS_1k) in the same position, with a $R^2 = 0.80$. The EDT_500 and RT_2k are almost as effective in that task with $R^2 = 0.78$ or 0.76, confirming the findings of the previous correlation analysis among measures. If the assumption that RASTI is a good predictor of speech intelligibility is correct (Brüel & Kjær 1986), then TS_1k will also be an accurate predictor of speech intelligibility. Even regardless of the receiver position within a church, RASTI was found to be easily predicted, with $R^2 = 0.74$, by the use of C80_2k. Loudness (L) does not appear as an important characteristic regarding RASTI values with $R^2 < 0.17$ supporting the idea that the intelligibility of speech, under reverberant conditions does not depend on Loudness. This agrees with the idea that speech intelligibility is related to the direct sound being at greater intensity than the reverberant sound. A prediction equation using three architectural parameters (nave width, nave height and the average absorption coefficient) was calculated to estimate, with $R^2 = 0.73$, the average RASTI in churches.

The effect of the architectural styles on RASTI values was found to show a negative trend regarding the first five styles i.e., speech intelligibility generally decreased until the Renaissance style with a strong improvement in the Baroque style (Reformation period). There were no statistically significant variations in the last two styles (19th-20th centuries). The Renaissance appears as the style with the lowest RASTI values and the Visigothic and

Baroque are the ones with the highest RASTI values. The use of pulpits without large canopies was found to increase the RASTI values. This was justified only by the decrease of the distance between the receiver and the source. Pulpits were found not to be a direct acoustical resource but only an indirect way to increase the intelligibility of speech by decreasing the distance from the speaker to the listener.

CHAPTER 7
BACH, A NEW BINAURAL MEASURE

7.1 Purpose

After having analyzed one of the two most important acoustical aspects of church services (speech), the second aspect, music is investigated. The purpose of this Chapter is to study the interaction between personal feelings regarding musical performances in this type of environment and a physical quantity to measure it.

7.2 Procedure

Binaural measurements that refer to the use of microphones located at the two ears of a manikin or human subject were also taken using a dual channel real time frequency analyzer. In the simultaneous analysis of signals it is no longer the signals themselves that are of primary interest, but rather the properties of the physical system responsible for the differences between them.

The idea was to use both instant spectra (channel A and channel B inputs) and their cross spectrum to find the coherence values. Channels A and B are microphones held outside both ears of a person in the center of the longitudinal axis of the church. A pink noise source was used with the loudspeaker in front of the altar at a height of 0.8 m and with sound pressure levels of 88-104 dB measured at the receiver.

The coherence gives a measure of the degree of linear dependence between the two signals as a function of frequency. It is calculated from the two autospectra and the cross spectrum. It can also be interpreted as a squared correlation coefficient expressing the degree of linear relationship between two variables. If the coherence is 1 there will be a perfectly

linear relationship between the signals at both ears. If it is 0, there is no relationship whatsoever between signals at the two ears (Randall 1987). Figure 7.1 shows one of the graphical outputs obtained. In each church, three spectra were recorded in the same position (only one position was used - in the middle of the longitudinal axis). The values were then averaged for further analysis (see Appendix N).

7.3 Subjective Analysis

Very basic qualitative information was collected in each church by an interview with the local priests and other members of the staff. Answers were requested to simple questions such as if the church had a good acoustics or good sound, if music sounded good in the church, if there were musical performances in the church, which type of musical performances occurred in the curch, if the performers like the sound of the church, etc. The churches were finally rated on a five level scale: very bad, bad, normal, good or very good acoustics (Appendix O). The subjective analysis was not the primary goal of this research so, this information was intended to be subsidiary.

7.4 BACH

7.4.1 Coherence

Using the coherence values obtained in twenty-eight 1/3 octave bands (Appendix O) a new measure was sought. Figure 7.2 presents the graphical representation of all bands considering the average of all churches tested. In this graph describing the general behavior of the coherence in all the churches tested, four areas can be identified. At very low frequencies the coherence is almost constant and equal to 1.0; from 200 to 800 Hz the coherence decreases with a roll-off of nearly 0.3/octave; at mid frequencies (1 to 2.5 kHz) there is a

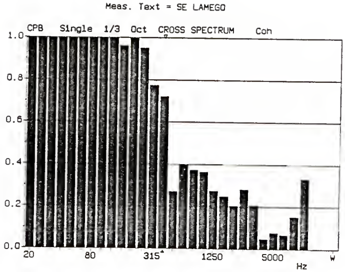


Figure 7.1 - Specimen of coherence data (y axis) with 1/3 octave frequency bands (x axis).

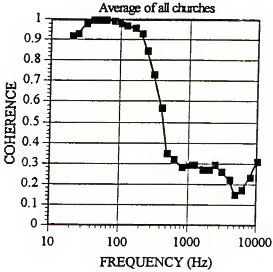


Figure 7.2 - Spectrum of averaged coherence (y axis) for all churches in 1/3 octave frequency bands (x axis).

constant level for the coherence around 0.28; finally to higher frequencies (3.15 to 10 kHz) a *V* shaped behavior appears with a drop to a coherence of 0.15 near 5 kHz.

To analyze which of these characteristics could be related to the subjective quality of the room (Appendix O), the Pearson correlation coefficients were calculated between Subjective rating and Coherence (28 frequency bands) - Table 7.1. The highest R was found with Coherence 3150 Hz (R = 0.552). But this is still a low R and other factors must be involved in the variance of the subjective quality ratings.

TABLE 7.1 - Pearson correlation coefficient between subjective quality rating and coherence.

Coherence	R	Coherence	R	Coherence	R	Coherence	R
20	0.145	100	-0.192	500	0.126	2500	0.380
25	-0.049	125	0.204	630	0.212	**3150**	**0.552**
32	0.040	160	0.218	800	0.305	4000	0.392
40	-0.029	200	-0.039	1000	0.093	5000	0.412
50	0.033	250	-0.047	1250	-0.200	6300	0.410
63	-0.128	315	0.212	1600	0.327	8000	0.238
80	0.317	400	0.044	2000	0.337	10000	0.425

7.4.2 BACH Equations

The new binaural acoustical measure, was called BACH, Binaural Acoustic CoHerence. Studying the general behavior of the coherence values in churches (Figure 7.2), 22 ratios or combinations of coherence were tested to find the best suited to represent or explain the variance in the subjective quality scores. The formulas are presented in Table 7.2. To test the fitness of all those 22 formulas, Table 7.2 displays the R coefficients regarding the linear smoothing between the Subjective rating and $BACH_N$. The highest R was found using BACH11's formula (R = - 0.684). The plot of this relationship is shown in Figure 7.3. This is the measure sought.

TABLE 7.2 - The 22 BACH formulas tested.

BACH1 = (Coh80 + Coh400) / 2	BACH12 = (Coh250 - Coh400) / Coh400
BACH2 = (Coh80 + Coh400) / (Coh800 + Coh1000)	BACH13 = (Coh250 - Coh400) / Coh250
BACH3 = (Coh125 + Coh250) / (Coh500 + Coh1k)	BACH14 = (Coh200 - Coh400) / Coh400
BACH4 =(Coh80 + Coh125 + Coh400 + Coh.8k+ Coh1k) / 5	BACH15 = (Coh200 - Coh400) / Coh200
BACH5=(Coh80+Coh125+Coh.4k+Coh.8k+Coh1k)/(5.Coh.4k)	BACH16=(Coh250+Coh.5k)/(Coh1k+Coh2k)
BACH6 = (Coh200 + Coh630)	BACH17=(Coh500+Coh1k)/(Coh2k+Coh4k)
BACH7 = (Coh200 + Coh630) / 2	BACH18 = (Coh250x2 - Coh500) / Coh500
BACH8 = (Coh250 - Coh630) / Coh630	BACH19 = Average (all Coh)
BACH9 = (Coh120 + Coh200) / (Coh630 + Coh800)	BACH20 = (Coh250 - Coh500) / Coh500
BACH10=(Coh.1k+Coh125+Coh160)/(Coh.4k+Coh.5k+Coh630)	BACH21 = Coh3150 + Coh4k + Coh5k
BACH11= (Coh50+Coh63+Coh80)/(Coh3150+Coh4k+Coh5k)	BACH22 = Coh3150 + Coh4k

TABLE 7.3 - Pearson correlation coefficients between subjective quality rating and $BACH_N$.

BACHn	R	BACHn	R	BACHn	R	BACHn	R
BACH1	0.093	BACH7	-0.219	BACH13	-0.079	BACH19	0.466
BACH2	-0.142	BACH8	-0.079	BACH14	-0.133	BACH20	-0.049
BACH3	-0.056	BACH9	-0.146	BACH15	-0.057	BACH21	0.573
BACH4	0.203	BACH10	-0.115	BACH16	-0.215	BACH22	0.538
BACH5	-0.104	**BACH11**	**-0.684**	BACH17	-0.339		
BACH6	-0.202	BACH12	-0.136	BACH18	-0.047		

7.4.3 BACH Analysis

7.4.3.1 The formula

Considering the ratings of acoustical quality by the priests of the churches, this R = -0.684 seems very reasonable to accept as a good relationship and supports the idea that subjective quality in churches regarding music can be assessed by the use of this new binaural measure. Therefore it seems that the overall subjective quality of churches for music can be inversely proportional to the following formula.

BACH = (Coh 50 + Coh 63 + Coh 80) / (Coh 3150 + Coh 4000 + Coh 5000)

by the next relation:

SUBJECTIVE = 5.374 - 0.310 BACH (Standard error of estimate = 0.88);

or

BACH = 11.229 - 1.511 SUBJECTIVE (Standard error of estimate = 1.9).

That is, the greater the difference between the coherence at the high and very low frequencies, the lower the church was rated regarding the overall subjective impression of music quality. The explanation for this result is hypothesized to be in the combination of several factors. Considering that not many musical instruments use those high frequencies (4 and 5 kHz), it is perhaps the effect of overtones or upper partials that it is present. It may also be the effects in the perception of treble and timbre or tone color that are also been weighted. In fact only a few instruments such as the xylophone, glockenspiel, harp, piccolo and naturally the organ can give such high notes. Or it may be that a similarity of sounds at both ears, over a wide range of frequencies, are considered to be preferable in live performances as opposed to the enjoyment of a musical piece when listened to using stereo headphones or loudspeakers.

It does not appear that this effect can be very important in explaining speech reception because those frequencies (3 to 6 kHz) are above the frequencies most significant to the understanding of speech. For most speech communication the critical frequency range is 300-3000 Hz although some speech cues occur as high as 8 kHz. Some of these facts describe subtle details of listening to music. It is questionable if the subjective ratings obtained could descriminate. More data is necessary to validate a more positive explanation.

7.4.3.2 Individual church analysis

Figure 7.4 presents the analyses of individual churches in two comparison examples of the coherence spectra found. In these Figures the dark and clear symbols represent respectively the churches rated *5* (Very Good) and *1* (Very Bad). Table 7.4 complements these two Figures. In both of the churches rated Very Bad there is a drop in the coherence values

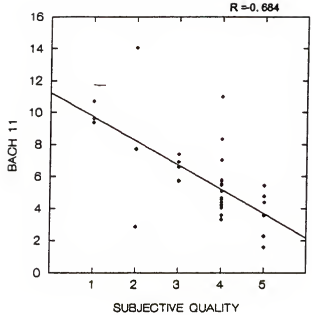


Figure 7.3 - Plot of subjective quality ratings (1-V. Bad, 2-Bad, 3-Normal, 4-Good, 5-V. Good) vs. the best BACH formula with linear regression model and correlation coefficient.

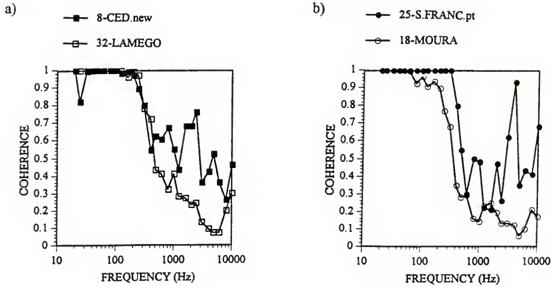


Figure 7.4 - Two pairwise comparisons of coherence spectra (dark/clear symbols relate to Very Good/Very Bad subjective quality ratings).
a) Church 8 - *Cedofeita New* (Contemporary) vs. Church 32 - *Sé Lamego* (Romanesque);
b) Church 25 - *S. Francisco,* Porto (Baroque) vs. Church 18 - *Moura* (Manueline).

around 5 kHz. By comparison, both churches rated Very Good present a peak in the coherence values between 2.5 and 4 kHz.

TABLE 7.4 - BACH results for a 4 church example.

CHURCH	SUBJECTIVE QUALITY	BACH
8 - Cedofeita new	*5 - Very Good*	2.3
18 - Moura	*1 - Very Bad*	9.6
25 - S. Francisco/Porto	*5 - Very Good*	1.6
32 - Lamego	*1 - Very Bad*	10.7

7.4.3.3 ANOVA tests

ANOVA tests were performed to examine the significance of the differences among the groups of equal subjective quality ratings. The three options are plotted in Figure 7.5 and the ANOVA results are expressed in Table 7.5. The three options were:

OPTION A - 5 groups of equal subjective quality (*1* to *5* in Table 7.1);

OPTION B - 3 groups of equal subjective quality, labeled:

1 - BAD (= *1* + *2* of option A)

3 - NORMAL (= *3* of option A)

5 - GOOD (= *4* + *5* of option A);

OPTION C - 2 groups equal of subjective quality, labeled:

2 - BAD (= *1* + *2* + *3* of option A)

4 - GOOD (= *4* + *5* of option A).

TABLE 7.5 - Summary of ANOVA results for 3 options of grouping regarding the subjective quality. Number of pairwise comparisons found statistically different at various p-value levels.

OPTION	GROUPS	Number of Pairwise Comparisons				
		p-value< 0.05	p-value< 0.10	p-value< 0.15	p-value< 0.20	Max.
A	5	3	5	6	6	10
B	3	1	1	2	3	3
C	2	1	1	1	1	1

Using Table 7.5, the conclusion is that the five groups system of rating (*1* to *5*) is too narrow to give statistically significant differences (with a p-value < 0.20). The use of a three group rating method (Figure 7.5b) gives statistically differences in all possible pairwise comparisons (for a p-value < 0.20). The use of a two group rating method (Figure 7.5c) gives a statistically difference in the only possible pairwise comparison (but now for a p-value < 0.05). Therefore it can be stated that a three group rating of subjective quality in churches in the method used in this study is an acceptable choice.

7.4.3.4 General linear model

In order to verify the importance of all the parameters in the subjective ratings, a general linear model was performed. The goal was to relate the SUBJECTIVE rating to some of the other parameters used throughout this study. Therefore the model was done with the 28 coherence bands, the 39 acoustical measures (all frequency bands), the 15 architectural parameters and the 22 BACH formulas for a total of 104 parameters. With an α-to-enter/remove equal to 0.05 the final model using a forward stepwise procedure only presented BACH11 as a predictor of the SUBJECTIVE rating (with $R^2 = 0.47$ and a standard error of the estimate = 0.88). Using an α-to-enter/remove equal to 0.10 the final predictors will now include $BACH_{11}$ and COH80 but the R^2 only improved to 0.52 with a standard error of the estimate = 0.84. Consequently, no other parameter tested in this study could be used as a subsitute for BACH to give the same type of information. This increases the validity and interest of this new measure and its individuality.

7.5 BACH and the Acoustical Measures

To check the relationship between BACH and the acoustical measures, the Pearson correlation coefficients were calculated for all the octave bands involved. Table 7.6 shows the values found. Figure 7.6a presents the plot of the highest correlation found (with TS 4 kHz).

With the results displayed in Table 7.6 (and Figure 7.6a) there are no strong and evident relations between any of the 39 acoustical measures and the new binaural measure. This increases its individuality.

TABLE 7.6 - Pearson correlation coefficients for the relationship between BACH and the acoustical measures.

Measure	R	Measure	R	Measure	R	Measure	R
RT 125	0.315	EDT 2k	0.513	D 500	-0.364	L 125	0.033
RT 250	0.299	EDT 4k	0.524	D 1k	-0.443	L 250	0.040
RT 500	0.396	C80 125	-0.296	D 2k	-0.456	L 500	0.035
RT 1k	0.436	C80 250	-0.163	D 4k	-0.440	L 1k	0.052
RT 2k	0.494	C80 500	-0.391	TS 125	0.332	L 2k	0.021
RT 4k	0.517	C80 1k	-0.504	TS 250	0.305	L 4k	-0.105
EDT 125	0.280	C80 2k	-0.543	TS 500	0.433	BR_RT	-0.162
EDT 250	0.284	C80 4k	-0.485	TS 1k	0.507	BR_L	-0.006
EDT 500	0.410	D 125	-0.206	TS 2k	0.538	RASTI	-0.481
EDT 1k	0.473	D 250	-0.006	**TS 4k**	**0.544**		

7.6 BACH and the Architectural Parameters

To check the relationship between BACH and the architectural parameters, the Pearson correlation coefficients were calculated for all the fifteen architectural parameters. Table 7.7 shows the values found. Figure 7.6b presents the plot of the highest correlation found (with ALPHA AVERAGE). With the results displayed in Table 7.7 (and Figure 7.6b) there are no evident relationship between any of the fifteen architectural parameters and the new binaural measure. This again, augments its uniqueness.

TABLE 7.7 - Pearson correlation coefficients for the relationships between BACH and the fifteen architectural parameters.

PARAMETER	R	PARAMETER	R	PARAMETER	R
VOLUME TOTAL	-0.016	LENGTH NAVE	0.084	WIDTH AVG.	-0.111
VOLUME NAVE	-0.004	HEIGHT MAXIMUM	0.075	SEATS	-0.009
AREA TOTAL	-0.046	HEIGHT NAVE avg.	0.183	ABSORPTION TOTAL	-0.253
AREA NAVE	-0.037	HEIGHT AVG. TOTAL	0.158	R LOCAL	-0.271
LENGTH MAXIMUM	0.148	WIDTH NAVE	-0.080	**ALPHA AVG.**	**-0.293**

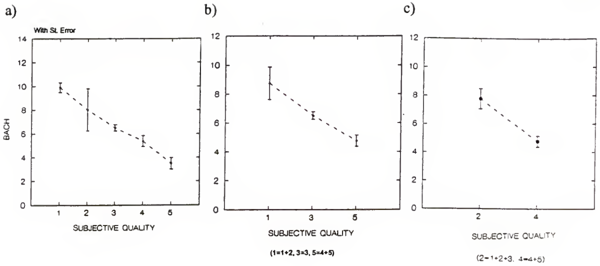


Figure 7.5 - Plot of BACH vs. three different methods of grouping subjective quality ratings with standard error confidence interval.
a) 5 level scale (1-V. Bad, 2-Bad, 3-Normal, 4-Good, 5-V. Good);
b) 3 level scale (1-Bad, 2-Normal, 3-Good; c) 2 level scale (1-Bad, 2-Good).

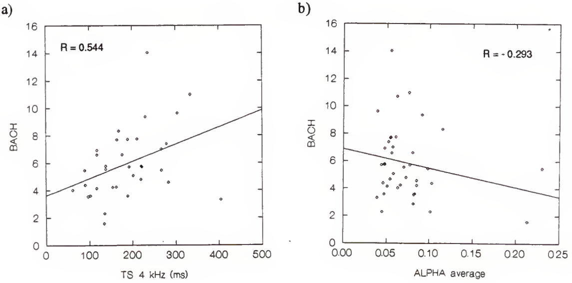


Figure 7.6 - Plots of BACH vs. the two quantities with the highest correlation coefficient found.
a) Vs. TS_4 kHz, the highest correlation among the acoustical measures; b) Vs. Average absorption coefficient, the highest correlation among the architectural parameters.

7.7 Summary

Using binaural measurements and subjective information collected in these churches, Binaural Acoustical CoHerence (BACH), a new binaural measure was presented as a ratio of coherence values (1/3 octave bands) between low (50, 63 and 80 Hz) and high (3.15, 4 and 5 kHz) frequencies. It was found to be orthogonal among the other 104 acoustical measures and architectural parameters ($R^2_i < 0.3$). A linear correlation coefficient near 0.7 was found between the BACH measure and a five point subjective quality rating regarding music in churches (V. Bad, Bad, Normal, Good, and V. Good), supporting the hypothesis that this measure can be useful in predicting the subjective quality of music heard in churches. A three point (Bad, Normal, and Good) method of rating the subjective quality of music in churches was found to be more acceptable than the five points used.

CHAPTER 8
CONCLUSIONS

This investigation revealed one critical area of acoustics in churches: the relationships of basic architectural styles, dimensions and materials of churches to detailed acoustical measurements made at multiple locations within each room. The results of this work permit several conclusions.

A) - One of the major contributions of this study is the development of a comprehensive method of analysis of room acoustic measures in churches. This work provides important knowledge regarding basic methodology to use in this particular environment.

A large group of 41 heterogeneous but representative churches (in size, shape and architectural styles) was chosen. The number and locations of sound source and receivers was defined. Two sound source positions were established near the altar and in the middle of the congregation seating area. Five or six receiver locations were set as a reasonable number depending on the width of the church. For the RASTI measurements a slightly large number of locations may be needed. A frequency averaging method to calculate a representative single-number average was determined. The two octave frequency bands centered on the 500 and 1000 Hz were calculated to be the most useful regarding the analyses with architectural parameters. For the analyses among acoustical measures the six octave frequency bands (125 - 4000 Hz) were used because no real improvement was determined to exist with any of the other six averaging options tested. A comprehensive set of acoustical measures and simple architectural parameters was also defined.

Three groups of related acoustical measures were found in this study: RT/EDT/TS, C80/D and L. RT and EDT present a very high correlation ($|R| > 0.99$) as expected because they are similar quantities with comparable physical meaning. EDT and TS also show a strong relationship between them ($|R| > 0.94$). These two factors suggest that any of those three measures (RT, EDT or TS) can be used to predict the other two. The RT is a reasonable choice due to its clear physical meaning and traditional use in this area. However EDT is considered to be a better predictor of the sense of reverberance and is more useful if subjective analysis is desired. C80 and D are highly correlated ($|R| > 0.94$) mainly due to their comparable physical and mathematical design. The correlation between L and the other five measures is markedly low ($|R| < 0.37$) confirming the individuality of this measure among those six and indicates that this quantity should be included as one of the acoustical measures. From the acoustical measures used, the most significant or useful to characterize the acoustical environment of churches are: RT (or EDT if subjective studies are involved), C80 and L.

B) - Another major contribution of this study was the calculation of several prediction equations that will have a real impact as a useful tool in the acoustical design of churches. Prediction formulas were defined for relationships among acoustical measures, between acoustical measures and architectural parameters and for the RT using the Sabine equation with a proposed new algorithm for coupled spaces.

1 - Relationships among the acoustical measures were defined and prediction equations were calculated to estimate measures taken at individual locations within each room as well as the mean values in each church. It was found that nonlinear models give a slightly better prediction line than the linear models in the majority of the cases studied (70%). Among these, the logarithmic smooth presents a better fit in many cases, especially in those with the

C80 measure. This is due to the logarithmic mathematical characteristic of many of these measures.

There are significant differences between the correlation coefficient |R| results (1 to 68% higher |R| in the averaged data option) depending upon whether all the data or just room average data were used. Depending on the situation been studied, a single point measure or a room average value, the corresponding prediction equation should be used.

2 - Within and inter church differences in the data for the six acoustical measures and the effect of sound source position were also analyzed. The within church variation in RT and EDT data were found to be much smaller than the variation of other measures. The variation was four times smaller than the variation of the C80 or D measures. This agrees with the findings of similar studies in concert halls (Barron 1994). In general, the spatial variation in the acoustical measures made in churches shows important similarities among all churches. Nevertheless, there are differences among churches that may be attributable to the architectural characteristics of each room, especially to differences in size. It was found that the differences among the mean values of the acoustical measures made in churches were significant in nearly 80% of the cases for the RT and EDT data and 61% to 75% in C80, TS and L data. However, there were only significant differences in the mean values of D in less than half of the churches because the internal variation of their values were relatively higher than the spatial variation of other measures. Therefore RT was found to be the most significant single measure to characterize a church as it is for concert halls (Barron 1994).

3 - The effect of fifteen architectural parameters on these acoustical measures was investigated. Prediction equations were calculated to estimate mean acoustical measures. Simple nonlinear models gave only a slightly better ($\Delta R^2 < 0.14$) prediction fit than the linear models in the majority (70%) of the cases studied. Among these, the logarithmic smooth

presents a better fit in many cases (C80, D and L). This is due to the logarithmic mathematical characteristic of many of the measures.

General linear models using only two to five architectural parameters were calculated to predict the six main acoustical measures with 71% (RT and EDT) to 85% (C80) of the variance explained and relatively small standard errors of the estimates. The bass ratios could not be reasonably predicted with the use of this set of architectural parameters ($R^2 \leq 0.35$). The use of the expected values for some acoustical measures found by the use of the classical diffuse field theory equations largely increased the fitness of the predictions models from $R^2 = 0.944$ (for C80) to $R^2 = 0.996$ (for EDT).

4 - The use of the classical reverberation time equations (Sabine and Eyring) was tested to estimate the measured reverberation times in this sample of churches. The Eyring equation gives slightly better results than the Sabine equation in predicting the RT when the effect of coupled spaces is not considered. Two trends were clearly distinguishable in the RT values indicating a need for a coupled spaces' analysis in the prediction of RT in churches that could better explain that difference between predicted and measured RTs.

The effect of coupled spaces was analyzed and a new algorithm for the application of the Sabine equation in churches was developed producing an average of 16% in the differences between the predicted and real RTs compared to a 71% difference using the standard Sabine equation. Coupled spaces (CS) were found to act as windows with a characteristic α depending on their dimensions $\{\alpha_{CS} = \tanh\ [a\ (l/w-b)]\}$. The recesses in churches were grouped in three types: main altar area, chapels and lateral aisles. Each type of coupled space has a particular acoustical behavior with different *a* and *b* parameters in the equation above. It was found that those recesses only acted as coupled spaces if their length/opening_width > 0.6 or if the aisle_width/opening_height > 0.4 in lateral aisles.

The remaining differences found between the RTs predicted with this new algorithm and the measured RTs were hypothesized to be related to what was called a reverberant ceiling effect which is presumed to be due to a two-dimensional reverberant sound field that builds up near a very tall ceiling.

The new algorithm for the use of the Sabine equation in this type of building accounting for several distinct types of coupled spaces should allow much greater accuracy of estimated reverberation times.

C) - A new understanding of several topics unique to churches was also achieved as the effect of changing architectural styles in the values of several acoustical measures, the analysis of RASTI or the effect of pulpits or the definition of a new binaural parameter to assess subjective quality regarding music.

1 - An innovative study in this research is the historical analysis of how the values of several acoustical measures changed over time, through the evolving architectural styles, reflecting important changes in Church history. The churches were grouped in eight architectural styles. From the acoustical measures tested, conclusions were drawn on the effect of the evolution of the architectural styles through the last fourteen centuries. In general this study suggests that some changes in the acoustical measures in churches are related to changes in architectural styles. Statistically significant differences were found in churches regarding their architectural styles for the RT, EDT and TS measures and a visible trend seems to be present in their variation through time. An increase in the mean values of RT (or EDT) was found through the first five styles with a decrease in the Baroque style (Reformation period) and again a negative slope in the last two styles (the Vatican II period). The TS data behave similarly but with inverted slopes due to its physical characteristics. Changes in church music and other church practices and changes in the mean values of some acoustical measures seem

to have occurred in the same historical periods. RT and EDT appeared as the most suitable acoustical measures to identify differences in churches regarding their architectural styles.

2 - The use of RASTI in churches was studied and the relationships with acoustical and architectural parameters identified. It was found that the vast majority of churches have RASTI values below 0.45 giving a poor rating in the quality of speech intelligibility.

New relationships of RASTI with other acoustical measures were identified eliminating the previous idea that this index was an independent test among other measures. RASTI values within churches, in positions not in the direct field of the sound source, can be predicted by the use of TS at 1000 Hz (TS_1k) in the same position, with a $R^2 = 0.80$. The EDT_500 and RT_2k are almost as effective in that task with $R^2 = 0.78$ or 0.76, confirming the findings of the previous correlation analysis among measures. If the assumption that RASTI is a good predictor of speech intelligibility is correct (Brüel & Kjær 1986), then TS_1k will also be an accurate predictor of speech intelligibility. Regardless of the receiver position within a church, RASTI was found to be easily predicted (with $R^2 = 0.74$) by the use of C80_2k. Loudness (L) does not appear as an important characteristic regarding RASTI values with $R^2 < 0.17$ supporting the idea that the intelligibility of speech, under reverberant conditions does not depend on Loudness. This agrees with the idea that speech intelligibility is related to the direct sound being at greater intensity than the reverberant sound. A prediction equation using three architectural parameters (nave width, nave height and the average absorption coefficient) was calculated to estimate (with $R^2 = 0.73$) the average RASTI in churches.

The effect of the architectural styles on RASTI values was found to show a negative trend regarding the first five styles, i.e., speech intelligibility generally decreased until the Renaissance with a strong improvement in the Baroque style (Reformation period). There

were no statistically significant variations in the last two styles. The Renaissance appears as the style with the lowest RASTI values and the Visigothic and Baroque are the ones with the highest RASTI values. The use of pulpits without large canopies was found to increase the RASTI values. This was justified only by the decrease of the distance between the receiver and the source. Using unoccupied churches, pulpits were found not to be a direct acoustical resource but only an indirect way to increase the intelligibility of speech by decreasing the distance from the speaker to the listener.

3 - The definition of a new binaural acoustical measure is believed to be an important step in studying the interaction between personal feelings regarding musical performances in this type of environment and a physical quantity to measure it. Using binaural measurements and subjective information collected in these churches, BACH a new binaural measure (Binaural Acoustical CoHerence), was presented as a ratio of coherence values (1/3 octave bands) between low (50, 63 and 80 Hz) and high (3.15, 4 and 5 kHz) frequencies. It was found to be orthogonal among the other 104 acoustical measures and architectural parameters ($R^2_i < 0.3$). A linear correlation coefficient near 0.7 was found between the BACH measure and a five point subjective quality rating regarding music in churches, supporting the hypothesis that this measure can be useful in predicting the subjective quality of music heard in churches. A three point (bad, normal, and good) method of rating the subjective quality of music in churches was found to be more acceptable than the five points used (very bad, bad, normal, good, and very good).

The results of this study provide designers and researchers the basic information and tools to predict several acoustical measures in churches during the early stages of design and without the need of measurements in real buildings. Though this work has considerably

increased the understanding of the acoustics of churches, much exploration is still needed to answer more quantitatively some of the questions posed in this field.

CHAPTER 9
PATHS FOR FURTHER RESEARCH

Suggestions are given below for possible areas of further investigation related to the subject of this research.

For design purposes, there is a need to quantitatively know what the optimum values of each acoustical measure should be to provide for satisfactory listening conditions given the unique acoustical requirements found in churches. Subjective studies that parallel this research are needed to determine if the differences in acoustical measures found within and among churches are actually heard as significant differences by the people that use the buildings. Subjective studies can also be performed to identify if an acoustical quality of churches that can be related to a sense of mystique or dignity, usually associated with this type of environment, exists. Comparisons between objective and subjective evaluations would have to be obtained to validate the relationships found. This is an area where interdisciplinary collaboration is strongly needed.

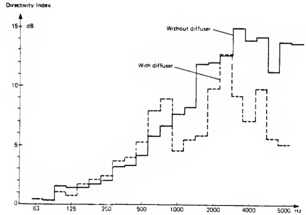
Another improvement in this study would be the use of occupied churches for the impulse response measurements. The data collected this way would permit, in certain analyses, a stronger validity in the conclusions drawn than the ones presented here done in unoccupied churches, especially in all areas where the absorption plays an important role. The continued development of the instrumentation, computer and testing techniques will soon allow the measurements done in this study to be easily made in occupied churches.

Collecting data from an even more substantial number of rooms encompassing a greater range of architectural diversity is essential. With an increased number of churches

tested, the within and among room variation of acoustical measures can be compared to architectural styles to analyze their similarities or differences and even their evolution through time. The prediction equations will also have a stronger validity and their application even more reliable.

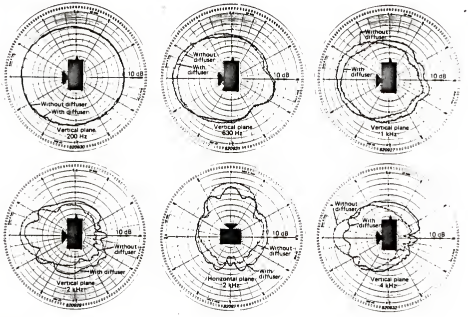
Various technical details could be improved in further research in this area. Other architectural parameters can be included in this analysis and their importance assessed in the influence they could have in the main acoustical measures especially the effect of indexes characterizing coupled spaces. The algorithm for the use of the Sabine equation can be improved by including a reverberant ceiling effect. Subjective studies can be done to improve the study of the validity of the RASTI as a speech intelligibility predictor in churches. More subjective studies can be done to improve the study of the validity of the BACH as a predictor of music quality in churches especially with the use of sound intensity probes. With this instrument it is possible to hear only the reflected sound in real churches and characterize the sound field subjectively based on these listening experiments. Cluster analysis techniques can be tested using all the acoustical measures and architectural parameters simultaneously to find reasonable groups of churches with similar and explainable characteristics.

APPENDIX A
TECHNICAL CHARACTERISTICS OF SOUND SOURCE USED



(Brüel & Kjær 1987, 15)

Figure A.1 - Typical directivity indices for the sound source (B&K type 4224 with and without diffuser).



(Brüel & Kjær 1987, 15)

Figure A.2 - Typical directivity characteristics for the sound source (B&K type 4224 with and without diffuser).

APPENDIX B
EFFECT OF NUMBER OF POSITIONS (PILOT STUDY)

A pilot study was conducted to study the within church variation of measures and how the number of positions at which measurements were recorded in each church affected the within church differences. The results are presented in Figure B.1. These graphs show the results found with data from all source-receiver positions, all frequency bands and all churches. In each graph the vertical axis is 40% of the respective maximum value for that measure found in the three churches. Using that method the plots can be visually related and the relative standard deviation compared. The three churches were measured using three different numbers of positions: *New Cedofeita* Church, 11 positions; *Old Cedofeita* Church, 8 positions; *Lapa* Church, 2 positions. For that reason, those Figures can also show the changes in the standard deviation due to the differences in the number of positions used. The within church variation regarding RT and EDT are very small compared with C80, D and TS. As expected, RT and EDT are the least variant of the five measures in this type of building as it also happens in concert halls (Barron 1994). The number of positions used does not significantly affect the results, except in the highest frequency bands, where a small increase is seen (Figures B.1a and B.1b). For C80 and TS data the within church variation is fairly large and increasing the number of positions, decreases the standard deviation significantly. Interestingly, the results obtained regarding the D measure do not agree with this trend in the lowest frequency bands.

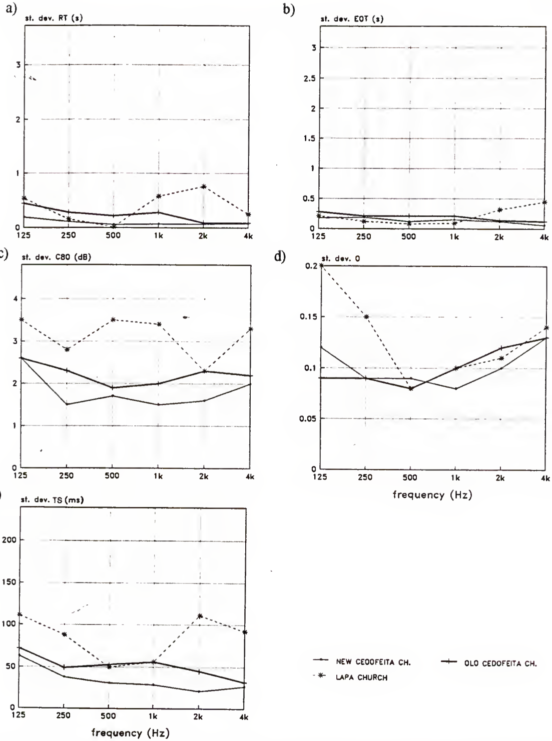


Figure B.1 - Standard deviation for values of six acoustical measures in the 3 churches of the pilot-study (*New Cedofeita*-11 receiver positions, *Old Cedofeita*-8 receiver positions, *Lapa*-2 receiver positions). The vertical axis is 40% of the maximum value for each particular acoustical measure in the churches.
a) RT; b) EDT; c) C80; d) D; e) TS.

The number of positions in each room is only an important factor for C80, D and TS measures. In these cases two positions is clearly insufficient and there are no significant improvements from choosing more than eight positions. Using this study the number of positions used in the research was set at five or six positions depending on the width of the church.

APPENDIX C
EFFECT OF WEIGHTING ACOUSTICAL MEASURES TO SEATING AREA REPRESENTED (PILOT STUDY)

There are several possible methods of averaging data among positions in churches. The goal of this analysis was to check if there are significant differences using two distinct methods of averaging and to use this knowledge in the later analysis of the data to be collected in the field-trip. The church studied was the *New Cedofeita* Church with data measured in 11 positions. This church was chosen because it had the largest number of positions measured. Figure C.1 shows the location of those 11 positions. The two averaging methods used were: Average 1 where all positions were weighted equally and Average 2 where the data were weighted by the number of seats surrounding each position. Table C.1 displays the weight and number of seats used.

As seen in Table C.1, the number of seats were not evenly distributed throughout the room to give a good data set for this analysis. Figures C.2 to C.4 present the results found. For each acoustical measure (RT, EDT, C80, D, TS and L) two graphs are shown: the left one presents the results using the two averaging methods and the right one compares the standard deviation (avg1) with the absolute value of the difference between the averages (avg1-avg2). For all the acoustical measures the differences found between the methods are much smaller than the respective standard deviation. The maximum value for the absolute difference between averages is only 40% the corresponding standard deviation. There are no significant differences in the RT and EDT data at all.

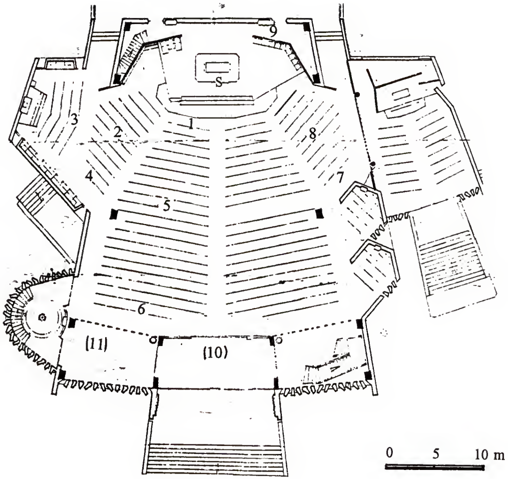


Figure C.1 - Plan of the *New Cedofeita* Church, Porto, Portugal with the location of the 11 receiver positions used in the pilot-study.

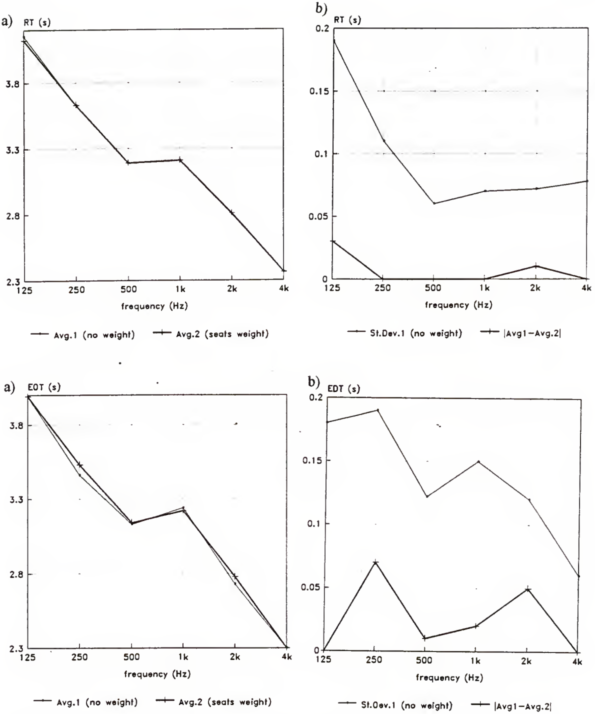


Figure C.2 - *New Cedofeita* Church test of two different methods for determining room average values of acoustical measures (Avg.1 - no weight, Avg.2 - seats weight) for the RT (top) and EDT (bottom) data.
a) Measured values as a function of frequency by the two methods; b) Standard deviation calculated using Avg.1 (above) compared with the absolute differences between Avg.1 and Avg.2 (|Avg.1 - Avg.2|) (below).

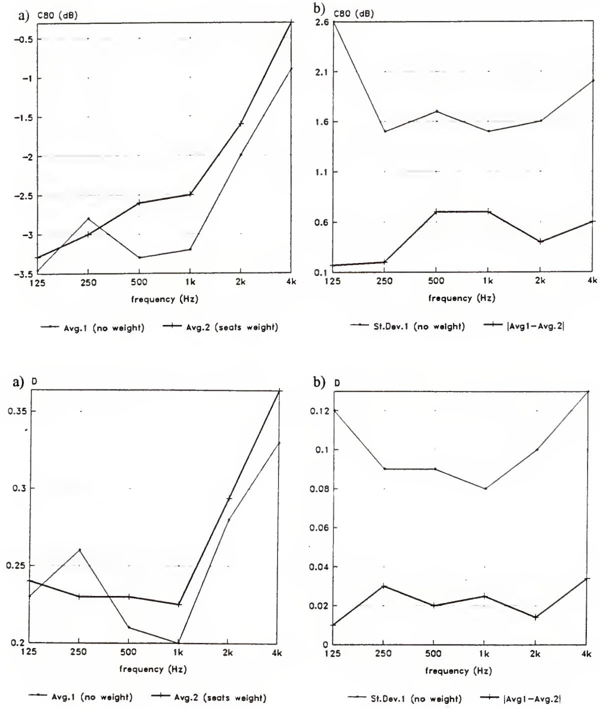


Figure C.3 - *New Cedofeita* Church test of two different methods for determining room average values of acoustical measures (Avg.1 - no weight, Avg.2 - seats weight) for the C80 (top) and D (bottom) data.
a) Measured values as a function of frequency by the two methods; b) Standard deviation calculated using Avg.1 (above) compared with the absolute differences between Avg.1 and Avg.2 (|Avg.1 - Avg.2|) (below).

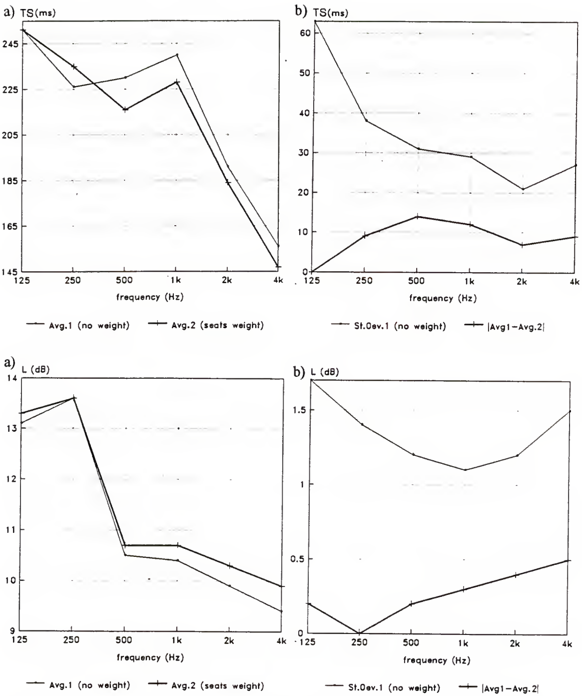


Figure C.4 - *New Cedofeita* Church test of two different methods for determining room average values of acoustical measures (Avg.1 - no weight, Avg.2 - seats weight) for the TS (top) and L (bottom) data.
a) Measured values as a function of frequency by the two methods; b) Standard deviation calculated using Avg.1 (above) compared with the absolute differences between Avg.1 and Avg.2 (|Avg.1 - Avg.2|) (below).

There is no need to be very careful in choosing the location for the microphones. Fairly evenly distributed positions will be sufficient. There is also no need to average the data by the number of seats involved. This was an important conclusion in choosing the position of each receiver location within the churches.

TABLE C.1 - Number of seats assigned for each position in the *New Cedofeita Church*, Porto, Portugal (pilot-study) for average method #2 (see church plan in Figure C.1).

POSITION NUMBER	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
NUMBER OF SEATS	36	23	20	18	155	130	25	28	1	69	75

APPENDIX D
ACOUSTICAL MEASURES WITH THE SEVEN AVERAGING METHODS

TABLE D.1 - Averaged data for each church using all six frequency bands-option 41_ALL.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	1.96	1.88	-0.9	0.30	138	20.4	0.99	2.53
2	ARMAMAR	2.31	2.23	-1.6	0.27	164	14.2	0.88	0.95
3	BAS. ESTRELA lisboa	7.53	7.14	-7.6	0.14	481	10.9	1.02	1.92
4	BRAVÃES	1.84	1.82	-0.6	0.31	134	17.4	1.07	2.38
5	BUSTELO	3.57	3.40	-3.8	0.22	241	12.2	0.86	0.43
6	CABEÇA SANTA	1.72	1.63	0.1	0.35	122	18.4	0.96	1.55
7	CAMINHA	2.45	2.38	-2.1	0.24	177	10.4	0.75	0.68
8	CEDOFEITA new porto	3.11	2.95	-3.2	0.24	207	11.1	1.25	1.60
9	CEDOFEITA old porto	3.61	3.48	-4.5	0.15	257	19.7	1.28	1.58
10	CETE	2.26	2.16	-2.3	0.23	168	16.7	1.00	1.61
11	CLÉRIGOS porto	3.26	2.89	-4.1	0.21	218	11.7	1.15	2.40
12	GOLEGÃ	3.13	2.97	-3.6	0.21	221	12.3	0.72	1.01
13	LAPA porto	5.36	4.90	-5.9	0.17	354	9.6	0.94	1.65
14	LEÇA	3.88	3.75	-5.2	0.17	278	11.2	0.90	1.60
15	LOUROSA	1.44	1.36	0.4	0.34	110	15.8	0.85	1.26
16	MÉRTOLA	4.78	4.69	-5.5	0.14	330	18.9	1.39	2.08
17	MISERICÓRDIA évora	2.11	2.06	-1.1	0.32	146	13.7	0.84	0.35
18	MOURA	6.47	6.24	-7.1	0.10	437	14.6	1.25	2.08
19	N. S. BOAVISTA porto	3.82	3.69	-4.0	0.20	262	14.4	1.30	1.91
20	PAÇO SOUSA	2.80	2.79	-4.7	0.17	233	10.7	0.91	1.11
21	SANT. SACRAM. porto	4.59	4.28	-5.2	0.17	303	13.8	0.91	1.04
22	S. CLARA porto	1.11	1.08	3.3	0.50	79	11.6	0.75	1.21
23	S. B. CASTRIS	3.03	2.92	-3.0	0.23	211	16.2	1.11	2.39
24	S. FRANCISCO évora	4.42	4.21	-5.1	0.22	286	8.5	0.94	-0.10
25	S. FRANCISCO porto	1.58	1.51	0.4	0.35	116	5.8	0.85	0.35
26	S. FRUTUOSO	1.14	1.04	2.6	0.44	82	19.9	1.07	2.63
27	S. GENS	1.66	1.56	0.5	0.37	115	22.2	1.34	2.85
28	S. P. FERREIRA	3.09	2.93	-4.4	0.13	228	14.9	1.02	2.13
29	S. P. RATES	2.87	2.77	-3.9	0.17	216	13.1	1.02	1.36
30	RORIZ	2.72	2.58	-2.5	0.26	189	16.0	0.93	3.30
31	S. ROQUE lisboa	3.48	3.28	-3.4	0.21	226	9.6	0.80	0.57
32	SÉlamego	3.80	3.53	-4.1	0.21	251	10.1	0.81	1.23
33	SÉ porto	3.38	3.25	-5.4	0.15	251	8.2	1.08	1.61
34	SILVES	3.62	3.57	-5.5	0.15	283	9.6	0.95	0.46
35	SEROA	4.43	4.33	-5.6	0.16	321	14.3	1.06	2.39
36	SERRA PILAR gaia	7.23	6.94	-6.9	0.14	495	12.8	1.04	1.19
37	TIBÃES	2.45	2.30	-1.8	0.28	170	9.4	0.88	1.31
38	VIANA ALENTEJO	2.84	2.80	-2.2	0.27	192	14.0	1.04	1.21
39	VILA DO BISPO	1.62	1.55	0.7	0.39	111	14.1	0.86	-0.40
40	V. N. AZEITÃO	2.08	2.01	-0.9	0.32	146	17.0	0.72	0.87
41	VOUZELA	1.34	1.26	1.5	0.42	98	14.1	0.92	4.21

TABLE D.2 - Averaged data for each church using only 2 and 4 kHz frequency bands-option 41_O24.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	1.83	1.81	-0.8	0.30	131	19.2	0.99	2.53
2	ARMAMAR	2.08	2.00	-1.4	0.28	155	12.5	0.88	0.95
3	BAS. ESTRELA lisboa	6.27	5.40	-6.1	0.18	392	8.4	1.02	1.92
4	BRAVÃES	1.64	1.63	-0.2	0.35	122	15.9	1.07	2.38
5	BUSTELO	3.10	3.00	-3.3	0.23	215	11.0	0.86	0.43
6	CABEÇA SANTA	1.67	1.61	0.2	0.35	121	17.7	0.96	1.55
7	CAMINHA	2.38	2.32	-2.3	0.24	176	9.2	0.75	0.68
8	CEDOFEITA new porto	2.42	2.36	-2.2	0.28	172	9.6	1.25	1.60
9	CEDOFEITA old porto	2.58	2.50	-3.0	0.19	198	17.3	1.28	1.58
10	CETE	2.22	2.17	-2.9	0.23	179	16.3	1.00	1.61
11	CLÉRIGOS porto	2.68	2.45	-3.7	0.23	193	10.6	1.15	2.40
12	GOLEGÃ	3.13	3.02	-4.3	0.17	235	11.3	0.72	1.01
13	LAPA porto	4.94	4.43	-5.1	0.20	323	7.8	0.94	1.65
14	LEÇA	3.27	3.03	-4.4	0.20	233	9.1	0.90	1.60
15	LOUROSA	1.35	1.34	-0.1	0.33	112	14.2	0.85	1.26
16	MÉRTOLA	3.29	3.22	-4.1	0.19	243	16.7	1.39	2.08
17	MISERICÓRDIA évora	2.20	2.16	-1.5	0.30	156	13.4	0.84	0.35
18	MOURA	4.53	4.28	-6.1	0.12	322	12.3	1.25	2.08
19	N. S. BOAVISTA porto	2.31	2.17	-1.2	0.31	160	11.5	1.30	1.91
20	PAÇO SOUSA	2.75	2.74	-4.4	0.18	224	10.0	0.91	1.11
21	SANT. SACR. porto	4.13	3.93	-5.2	0.16	286	12.1	0.91	1.04
22	STA. CLARA porto	1.14	1.13	2.5	0.47	83	10.5	0.75	1.21
23	S. B. CASTRIS	2.48	2.40	-2.1	0.27	180	14.0	1.11	2.39
24	S. FRANCISCO évora	3.57	3.31	-4.5	0.23	241	7.2	0.94	-0.10
25	S. FRANCISCO porto	1.46	1.42	0.7	0.37	107	5.2	0.85	0.35
26	S. FRUTUOSO	0.95	0.89	3.6	0.48	73	17.9	1.07	2.63
27	S. GENS	1.40	1.36	0.8	0.39	106	20.3	1.34	2.85
28	S. P. FERREIRA	2.59	2.46	-4.0	0.14	203	12.4	1.02	2.13
29	S. P. RATES	2.55	2.49	-3.6	0.19	202	11.8	1.02	1.36
30	RORIZ	2.36	2.29	-2.2	0.28	182	13.4	0.93	3.30
31	S. ROQUE lisboa	3.65	3.46	-3.8	0.20	246	9.0	0.80	0.57
32	SÉ lamego	3.23	3.04	-3.3	0.24	224	7.9	0.81	1.23
33	SÉ porto	2.69	2.57	-4.3	0.18	205	6.1	1.08	1.61
34	SILVES	3.20	3.09	-5.2	0.16	248	8.2	0.95	0.46
35	SEROA	3.78	3.70	-4.6	0.19	273	12.6	1.06	2.39
36	SERRA PILAR gaia	5.58	5.17	-5.3	0.19	374	10.7	1.04	1.19
37	TIBÃES	2.24	2.10	-1.8	0.27	164	7.8	0.88	1.31
38	VIANA ALENTEJO	2.31	2.32	-2.0	0.30	174	12.3	1.04	1.21
39	VILA DO BISPO	1.53	1.50	1.4	0.43	102	12.8	0.86	-0.40
40	V. N. AZEITÃO	2.25	2.22	-1.9	0.28	164	16.2	0.72	0.87
41	VOUZELA	1.24	1.25	1.5	0.41	97	12.1	0.92	4.21

TABLE D.3 - Averaged data for each church using 4 frequency bands, 125 to 1000 Hz, option 41_W24.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	2.02	1.90	-0.9	0.30	140	21.1	0.99	2.53
2	ARMAMAR	2.42	2.34	-1.7	0.27	168	15.0	0.88	0.95
3	BAS. ESTRELA lisboa	8.22	7.99	-8.5	0.11	526	11.9	1.02	1.92
4	BRAVÃES	1.95	1.91	-0.8	0.29	141	18.1	1.07	2.38
5	BUSTELO	3.79	3.59	-4.1	0.22	254	12.9	0.86	0.43
6	CABEÇA SANTA	1.75	1.63	0.1	0.36	121	19.0	0.96	1.55
7	CAMINHA	2.49	2.36	-2.1	0.24	178	11.0	0.75	0.68
8	CEDOFEITA new porto	3.47	3.25	-3.9	0.22	225	11.5	1.25	1.60
9	CEDOFEITA old porto	4.11	3.97	-5.4	0.13	287	21.2	1.28	1.58
10	CETE	2.28	2.15	-2.0	0.24	164	16.9	1.00	1.61
11	CLÉRIGOS porto	3.60	3.13	-3.9	0.22	227	12.6	1.15	2.40
12	GOLEGÃ	3.04	2.95	-3.3	0.23	216	12.7	0.72	1.01
13	LAPA porto	5.56	5.15	-6.1	0.17	368	10.7	0.94	1.65
14	LEÇA	4.15	4.08	-5.6	0.16	299	12.1	0.90	1.60
15	LOUROSA	1.48	1.38	0.5	0.34	111	16.4	0.85	1.26
16	MÉRTOLA	5.45	5.38	-6.2	0.12	370	19.9	1.39	2.08
17	MISERICÓRDIA évora	2.07	2.01	-0.8	0.32	141	13.9	0.84	0.35
18	MOURA	7.39	7.22	-7.6	0.10	495	15.7	1.25	2.08
19	N. S. BOAVISTA porto	4.57	4.45	-5.4	0.14	314	15.8	1.30	1.91
20	PAÇO SOUSA	2.81	2.79	-4.7	0.17	233	11.3	0.91	1.11
21	SANT. SACRAM. porto	4.78	4.42	-5.3	0.17	311	14.5	0.91	1.04
22	STA. CLARA porto	1.09	1.05	3.6	0.51	76.8	12.1	0.75	1.21
23	S. B. CASTRIS	3.31	3.18	-3.5	0.20	226	17.3	1.11	2.39
24	S. FRANCISCO évora	4.88	4.66	-5.3	0.22	309	9.2	0.94	-0.10
25	S. FRANCISCO porto	1.65	1.55	0.3	0.34	120	6.1	0.85	0.35
26	S. FRUTUOSO	1.24	1.11	2.1	0.41	87.3	20.9	1.07	2.63
27	S. GENS	1.79	1.66	0.2	0.35	122	23.3	1.34	2.85
28	S. P. FERREIRA	3.32	3.14	-4.6	0.13	239	16.1	1.02	2.13
29	S. P. RATES	3.03	2.90	-4.0	0.16	224	13.7	1.02	1.36
30	RORIZ	2.91	2.72	-2.6	0.25	193	17.2	0.93	3.30
31	S. ROQUE lisboa	3.40	3.20	-3.2	0.22	216	9.9	0.80	0.57
32	SÉ lamego	4.13	3.74	-4.4	0.20	264	11.0	0.81	1.23
33	SÉ porto	3.74	3.57	-5.9	0.13	274	8.9	1.08	1.61
34	SILVES	3.83	3.78	-5.4	0.15	294	10.4	0.95	0.46
35	SEROA	4.72	4.64	-6.0	0.14	342	15.0	1.06	2.39
36	SERRA PILAR gaia	7.97	7.75	-7.5	0.12	549	13.9	1.04	1.19
37	TIBÃES	2.56	2.40	-1.8	0.29	174	10.1	0.88	1.31
38	VIANA ALENTEJO	3.11	3.04	-2.3	0.26	201	14.9	1.04	1.21
39	VILA DO BISPO	1.65	1.58	0.3	0.36	116	14.5	0.86	-0.40
40	V. N. AZEITÃO	1.99	1.91	-0.5	0.33	139	17.3	0.72	0.87
41	VOUZELA	1.39	1.26	1.5	0.42	99.1	15.1	0.92	4.21

TABLE D.4 - Averaged data for each church using the 4 highest frequency bands, 500 to 4000 Hz, option 41_4H.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	1.93	1.91	-0.9	0.31	137	19.5	0.99	2.53
2	ARMAMAR	2.32	2.26	-2.0	0.25	171	13.5	0.88	0.95
3	BAS. ESTRELA lisboa	7.21	6.73	-8.0	0.13	484	9.6	1.02	1.92
4	BRAVÃES	1.76	1.76	-0.3	0.31	132	16.4	1.07	2.38
5	BUSTELO	3.61	3.49	-4.1	0.20	253	11.8	0.86	0.43
6	CABEÇA SANTA	1.73	1.69	-0.2	0.33	128	18.0	0.96	1.55
7	CAMINHA	2.62	2.55	-3.0	0.20	195	9.9	0.75	0.68
8	CEDOFEITA new porto	2.76	2.66	-3.2	0.24	198	10.2	1.25	1.60
9	CEDOFEITA old porto	3.10	2.98	-3.8	0.17	228	18.8	1.28	1.58
10	CETE	2.25	2.18	-2.9	0.21	178	16.2	1.00	1.61
11	CLÉRIGOS porto	3.01	2.77	-4.6	0.20	221	11.0	1.15	2.40
12	GOLEGÃ	3.38	3.26	-4.7	0.16	250	11.7	0.72	1.01
13	LAPA porto	5.33	4.99	-6.4	0.16	376	8.8	0.94	1.65
14	LEÇA	3.82	3.55	-5.6	0.16	275	10.2	0.90	1.60
15	LOUROSA	1.47	1.45	-0.4	0.30	120	15.0	0.85	1.26
16	MÉRTOLA	3.92	3.86	-4.9	0.16	286	17.8	1.39	2.08
17	MISERICÓRDIA évora	2.23	2.21	-1.8	0.29	159	13.6	0.84	0.35
18	MOURA	5.55	5.32	-6.9	0.10	391	13.5	1.25	2.08
19	N. S. BOAVISTA porto	3.15	2.99	-3.2	0.23	220	13.2	1.30	1.91
20	PAÇO SOUSA	2.85	2.88	-5.0	0.15	242	10.4	0.91	1.11
21	SANT. SACRAM. porto	4.57	4.38	-5.9	0.15	320	13.1	0.91	1.04
22	S. CLARA porto	1.19	1.19	2.1	0.44	87.2	11.0	0.75	1.21
23	S. B. CASTRIS	2.81	2.75	-3.0	0.23	206	15.1	1.11	2.39
24	S. FRANCISCO évora	4.30	4.08	-5.5	0.20	293	8.2	0.94	-0.10
25	S. FRANCISCO porto	1.62	1.58	-0.1	0.32	122	5.6	0.85	0.35
26	S. FRUTUOSO	1.07	0.97	3.1	0.47	76.6	18.8	1.07	2.63
27	S. GENS	1.46	1.42	0.7	0.38	108	21.1	1.34	2.85
28	S. P. FERREIRA	2.93	2.78	-4.5	0.12	223	13.7	1.02	2.13
29	S. P. RATES	2.78	2.70	-4.1	0.16	219	12.4	1.02	1.36
30	RORIZ	2.68	2.56	-2.7	0.25	196	14.5	0.93	3.30
31	S. ROQUE lisboa	3.71	3.58	-4.2	0.17	255	9.3	0.80	0.57
32	SÉ lamego	3.89	3.50	-4.3	0.19	257	9.1	0.81	1.23
33	SÉ porto	3.14	3.02	-5.6	0.13	244	7.1	1.08	1.61
34	SILVES	3.57	3.51	-6.0	0.12	286	9.2	0.95	0.46
35	SEROA	4.18	4.13	-5.6	0.16	310	13.2	1.06	2.39
36	SERRA PILAR gaia	6.71	6.45	-6.8	0.14	474	12.0	1.04	1.19
37	TIBÃES	2.48	2.34	-2.7	0.23	184	8.6	0.88	1.31
38	VIANA ALENTEJO	2.68	2.69	-2.3	0.26	192	13.3	1.04	1.21
39	VILA DO BISPO	1.65	1.62	0.8	0.39	113	13.8	0.86	-0.40
40	V. N. AZEITÃO	2.28	2.25	-1.7	0.28	164	16.5	0.72	0.87
41	VOUZELA	1.34	1.33	0.8	0.38	106	12.6	0.92	4.21

TABLE D.5 - Averaged data for each church using 4 medium frequency bands, 250 to 2000 Hz, option 41_4M.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	1.98	1.90	-0.8	0.31	137	20.2	0.99	2.53
2	ARMAMAR	2.35	2.28	-1.8	0.26	168	14.4	0.88	0.95
3	BAS. ESTRELA lisboa	7.93	7.65	-8.9	0.11	532	11.0	1.02	1.92
4	BRAVÃES	1.83	1.83	-0.7	0.29	137	17.4	1.07	2.38
5	BUSTELO	3.83	3.69	-4.6	0.19	266	12.5	0.86	0.43
6	CABEÇA SANTA	1.75	1.69	0.1	0.36	124	18.7	0.96	1.55
7	CAMINHA	2.66	2.59	-2.9	0.20	195	10.6	0.75	0.68
8	CEDOFEITA new porto	3.10	2.95	-3.5	0.23	212	10.9	1.25	1.60
9	CEDOFEITA old porto	3.59	3.49	-4.7	0.14	261	20.3	1.28	1.58
10	CETE	2.22	2.13	-2.0	0.24	166	16.5	1.00	1.61
11	CLÉRIGOS porto	3.37	3.01	-4.7	0.18	236	11.7	1.15	2.40
12	GOLEGÃ	3.26	3.13	-3.9	0.20	234	12.1	0.72	1.01
13	LAPA porto	5.58	5.27	-6.5	0.15	390	10.0	0.94	1.65
14	LEÇA	4.00	3.81	-5.8	0.15	289	11.1	0.90	1.60
15	LOUROSA	1.47	1.42	0.1	0.33	116	15.8	0.85	1.26
16	MÉRTOLA	4.69	4.64	-5.7	0.13	333	19.0	1.39	2.08
17	MISERICÓRDIA évora	2.20	2.17	-1.4	0.30	153	13.9	0.84	0.35
18	MOURA	6.55	6.37	-7.3	0.10	457	14.8	1.25	2.08
19	N. S. BOAVISTA porto	3.88	3.76	-4.6	0.18	274	14.6	1.30	1.91
20	PAÇO SOUSA	2.89	2.91	-5.0	0.16	244	11.0	0.91	1.11
21	SANT. SACRAM. porto	4.77	4.51	-5.8	0.15	324	14.1	0.91	1.04
22	S. CLARA porto	1.17	1.15	2.4	0.45	85	11.6	0.75	1.21
23	S. B. CASTRIS	3.06	3.01	-3.4	0.21	221	16.3	1.11	2.39
24	S. FRANCISCO évora	4.74	4.55	-5.7	0.20	317	9.0	0.94	-0.10
25	S. FRANCISCO porto	1.70	1.63	-0.2	0.31	124	5.8	0.85	0.35
26	S. FRUTUOSO	1.16	1.05	2.6	0.45	81	19.9	1.07	2.63
27	S. GENS	1.63	1.54	0.7	0.38	113	22.3	1.34	2.85
28	S. P. FERREIRA	3.16	2.93	-4.7	0.12	229	15.0	1.02	2.13
29	S. P. RATES	2.93	2.82	-4.2	0.16	225	13.1	1.02	1.36
30	RORIZ	2.84	2.66	-2.6	0.25	195	15.8	0.93	3.30
31	S. ROQUE lisboa	3.61	3.50	-4.0	0.18	246	9.6	0.80	0.57
32	SÉ lamego	4.12	3.73	-5.0	0.17	275	10.2	0.81	1.23
33	SÉ porto	3.53	3.40	-6.2	0.12	267	8.2	1.08	1.61
34	SILVES	3.81	3.77	-6.2	0.12	304	10.0	0.95	0.46
35	SEROA	4.58	4.52	-5.9	0.15	336	14.3	1.06	2.39
36	SERRA PILAR gaia	7.54	7.32	-7.6	0.11	540	13.0	1.04	1.19
37	TIBÃES	2.59	2.47	-2.5	0.24	187	9.5	0.88	1.31
38	VIANA ALENTEJO	2.95	2.92	-2.4	0.25	202	14.2	1.04	1.21
39	VILA DO BISPO	1.69	1.63	0.5	0.38	116	14.5	0.86	-0.40
40	V. N. AZEITÃO	2.20	2.12	-1.2	0.30	155	17.0	0.72	0.87
41	VOUZELA	1.36	1.32	0.9	0.38	105	13.5	0.92	4.21

TABLE D.6 - Averaged data for each church using only 3 frequency bands, 500 to 2000 Hz, option 41_3F.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	2.00	1.97	-0.9	0.31	139	19.5	0.99	2.53
2	ARMAMAR	2.44	2.39	-2.3	0.24	180	14.1	0.88	0.95
3	BAS. ESTRELA lisboa	7.76	7.39	-8.9	0.11	532	10.3	1.02	1.92
4	BRAVÃES	1.83	1.83	-0.7	0.30	136	16.8	1.07	2.38
5	BUSTELO	3.84	3.75	-4.8	0.18	272	12.1	0.86	0.43
6	CABEÇA SANTA	1.77	1.75	-0.3	0.33	132	18.2	0.96	1.55
7	CAMINHA	2.75	2.69	-3.3	0.19	206	10.4	0.75	0.68
8	CEDOFEITA new porto	2.91	2.80	-3.5	0.23	209	10.5	1.25	1.60
9	CEDOFEITA old porto	3.35	3.22	-4.2	0.16	245	19.6	1.28	1.58
10	CETE	2.31	2.24	-2.7	0.22	178	16.0	1.00	1.61
11	CLÉRIGOS porto	3.25	2.93	-4.9	0.18	234	11.1	1.15	2.40
12	GOLEGÃ	3.52	3.42	-4.8	0.15	260	12.0	0.72	1.01
13	LAPA porto	5.60	5.33	-6.8	0.15	402	9.4	0.94	1.65
14	LEÇA	4.05	3.81	-6.1	0.13	297	10.8	0.90	1.60
15	LOUROSA	1.54	1.52	-0.7	0.29	126	15.4	0.85	1.26
16	MÉRTOLA	4.22	4.17	-5.3	0.14	308	18.4	1.39	2.08
17	MISERICÓRDIA évora	2.27	2.28	-1.9	0.28	162	13.7	0.84	0.35
18	MOURA	6.08	5.84	-7.2	0.10	426	14.1	1.25	2.08
19	N. S. BOAVISTA porto	3.50	3.35	-4.1	0.19	247	13.9	1.30	1.91
20	PAÇO SOUSA	2.92	2.99	-5.4	0.14	253	10.7	0.91	1.11
21	SANT. SACRAM. porto	4.84	4.65	-6.1	0.14	339	13.6	0.91	1.04
22	S. CLARA porto	1.23	1.22	1.9	0.43	90	11.3	0.75	1.21
23	S. B. CASTRIS	2.98	2.94	-3.4	0.21	220	15.6	1.11	2.39
24	S. FRANCISCO évora	4.71	4.49	-5.9	0.19	318	8.8	0.94	-0.10
25	S. FRANCISCO porto	1.70	1.66	-0.3	0.31	127	5.7	0.85	0.35
26	S. FRUTUOSO	1.14	1.02	2.9	0.48	77	19.2	1.07	2.63
27	S. GENS	1.50	1.45	0.8	0.38	108	21.5	1.34	2.85
28	S. P. FERREIRA	3.14	2.97	-4.9	0.11	234	14.4	1.02	2.13
29	S. P. RATES	2.91	2.84	-4.4	0.16	228	12.8	1.02	1.36
30	RORIZ	2.86	2.71	-2.9	0.24	204	15.1	0.93	3.30
31	S. ROQUE lisboa	3.80	3.72	-4.5	0.16	265	9.4	0.80	0.57
32	SÉ lamego	4.16	3.74	-4.9	0.17	276	9.7	0.81	1.23
33	SÉ porto	3.36	3.24	-6.2	0.11	261	7.6	1.08	1.61
34	SILVES	3.76	3.75	-6.6	0.10	308	9.7	0.95	0.46
35	SEROA	4.40	4.36	-5.9	0.15	330	13.6	1.06	2.39
36	SERRA PILAR gaia	7.34	7.10	-7.6	0.12	527	12.6	1.04	1.19
37	TIBÃES	2.60	2.46	-2.9	0.22	194	9.1	0.88	1.31
38	VIANA ALENTEJO	2.87	2.87	-2.4	0.26	200	13.8	1.04	1.21
39	VILA DO BISPO	1.72	1.68	0.5	0.37	118	14.2	0.86	-0.40
40	V. N. AZEITÃO	2.33	2.29	-1.8	0.28	168	16.8	0.72	0.87
41	VOUZELA	1.40	1.39	0.4	0.36	111	12.8	0.92	4.21

TABLE D.7 - Averaged data for each church using 2 frequency bands, 500 and 1000 Hz, option 41_2F.

	CHURCH	RT (s)	EDT (s)	C80 (dB)	D	TS (ms)	L (dB)	BR_RT	BR_L
1	ALMANSIL	2.03	2.01	-1.0	0.31	142	19.8	0.99	2.53
2	ARMAMAR	2.57	2.52	-2.7	0.22	188	14.5	0.88	0.95
3	BAS. ESTRELA lisboa	8.14	8.07	-10.0	0.09	577	10.9	1.02	1.92
4	BRAVÃES	1.88	1.89	-0.9	0.28	141	16.9	1.07	2.38
5	BUSTELO	4.07	3.98	-5.4	0.16	291	12.7	0.86	0.43
6	CABEÇA SANTA	1.79	1.77	-0.6	0.32	134	18.2	0.96	1.55
7	CAMINHA	2.85	2.78	-3.7	0.17	215	10.6	0.75	0.68
8	CEDOFEITA new porto	3.09	2.96	-4.2	0.21	224	10.7	1.25	1.6
9	CEDOFEITA old porto	3.62	3.46	-4.5	0.15	259	20.4	1.28	1.58
10	CETE	2.28	2.20	-2.9	0.20	177	16.1	1.00	1.61
11	CLÉRIGOS porto	3.35	3.08	-5.4	0.16	249	11.4	1.15	2.40
12	GOLEGÃ	3.62	3.51	-5.0	0.14	265	12.2	0.72	1.01
13	LAPA porto	5.72	5.55	-7.6	0.12	428	9.8	0.94	1.65
14	LEÇA	4.37	4.07	-6.7	0.11	317	11.3	0.90	1.60
15	LOUROSA	1.60	1.55	-0.8	0.28	128	15.8	0.85	1.26
16	MÉRTOLA	4.56	4.50	-5.7	0.13	330	18.8	1.39	2.08
17	MISERICÓRDIA évora	2.26	2.27	-2.1	0.27	163	13.7	0.84	0.35
18	MOURA	6.57	6.37	-7.7	0.09	460	14.6	1.25	2.08
19	N. S. BOAVISTA porto	3.98	3.82	-5.1	0.16	280	14.9	1.30	1.91
20	PAÇO SOUSA	2.94	3.03	-5.7	0.12	260	10.8	0.91	1.11
21	SANT. SACRAM. porto	5.02	4.84	-6.5	0.13	354	14.0	0.91	1.04
22	S. CLARA porto	1.25	1.25	1.8	0.41	92	11.5	0.75	1.21
23	S. B. CASTRIS	3.14	3.10	-3.9	0.19	233	16.1	1.11	2.39
24	S. FRANCISCO évora	5.04	4.85	-6.5	0.17	344	9.3	0.94	-0.10
25	S. FRANCISCO porto	1.78	1.75	-1.0	0.27	137	6.0	0.85	0.35
26	S. FRUTUOSO	1.20	1.06	2.5	0.46	80	19.6	1.07	2.63
27	S. GENS	1.53	1.47	0.7	0.38	109	21.9	1.34	2.85
28	S. P. FERREIRA	3.28	3.11	-5.1	0.10	242	15.0	1.02	2.13
29	S. P. RATES	3.00	2.92	-4.7	0.14	236	13.1	1.02	1.36
30	RORIZ	3.01	2.82	-3.3	0.23	210	15.6	0.93	3.30
31	S. ROQUE lisboa	3.77	3.71	-4.6	0.15	264	9.6	0.80	0.57
32	SÉ lamego	4.55	3.95	-5.4	0.15	291	10.4	0.81	1.23
33	SÉ porto	3.59	3.47	-6.9	0.08	283	8.1	1.08	1.61
34	SILVES	3.93	3.93	-6.9	0.09	323	10.1	0.95	0.46
35	SEROA	4.57	4.57	-6.6	0.13	348	13.8	1.06	2.39
36	SERRA PILAR gaia	7.83	7.74	-8.2	0.10	574	13.3	1.04	1.19
37	TIBÃES	2.72	2.58	-3.6	0.19	205	9.5	0.88	1.31
38	VIANA ALENTEJO	3.05	3.06	-2.7	0.23	211	14.3	1.04	1.21
39	VILA DO BISPO	1.78	1.74	0.1	0.35	124	14.8	0.86	-0.40
40	V. N. AZEITÃO	2.31	2.28	-1.6	0.29	165	16.9	0.72	0.87
41	VOUZELA	1.45	1.42	0.1	0.34	115	13.0	0.92	4.21

APPENDIX E
THE SEARCH FOR A REPRESENTATIVE SINGLE NUMBER AVERAGE FOR RELATIONSHIPS AMONG ACOUSTICAL MEASURES

The analysis of the behavior of each of the seven options of averaging concerning their influence in the results of the relationships among the acoustical measures are presented here. Figure E.1 presents the mean values for each acoustical measure and for each octave frequency band, with a one standard deviation interval shown. No octave frequency band seems particularly suited to be excluded from their particular role in a room-average procedure. To examine which of these seven options is the most suitable in this situation, the correlation coefficients among all measures were determined for each of the averaging options. Table E.1 presents the highest R found in each of the fifteen pairs of acoustical measures. Table E.2 shows the number of times each of the seven averaging options were chosen as the best fit in the calculation of Table E.1.

Table E.3 presents the results concerning the influence of each of the seven frequency averaging options on the Pearson correlation coefficients (linear relationships) among the acoustical measures. As previously stated this analysis is not as important as the one (done later) concerning the relationships between the acoustical measures and architectural parameters because there a single-number average is definitely needed. Among the acoustical measures, each value can be compared with its correspondent in the same position with the same frequency. Nevertheless this analysis can complement the results found later. In Table E.3, 28 relations between acoustical measures are listed and for each one the squared correlation coefficient is given for the seven frequency-averaging options. Using this table where the highest values in a row are bold faced if $R^2 > 0.60$ - significant linear relationship,

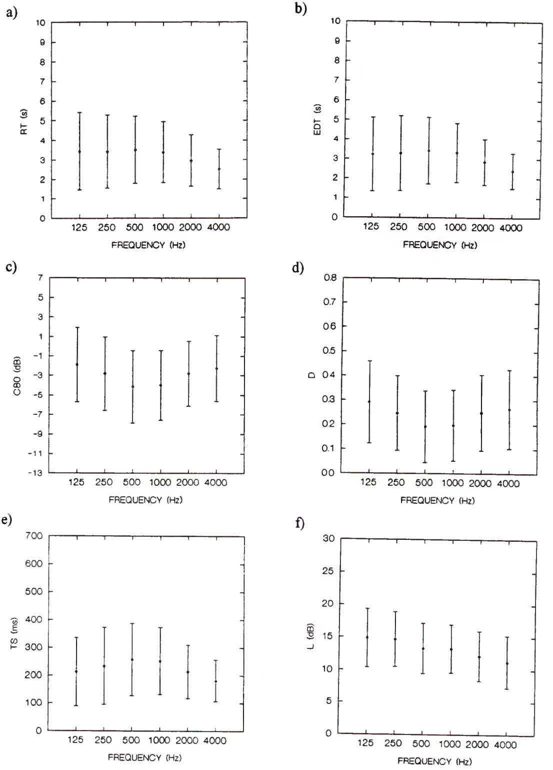


Figure E.1 - Mean values for each acoustical measure with one standard deviation confidence interval by octave frequency bands (all source/receiver positions considered).
a) RT; b) EDT; c) C80; d) D; e) TS; f) L.

it can be seen that small differences exist among the seven options. Just one option, the 2k/4k, shows a small disadvantage compared with the others. This analysis substantiates using any one of the types of averaging methods tested. Using Tables E.1 to E.3 there is no clear evidence to support the use of a particular method of averaging.

TABLE E.1 - R values among acoustical measures for best fits regarding seven options of averaging methods (in parenthesis).

Measure	RT	EDT	C80	D	TS
EDT	0.999 (ALL)	-	-	-	-
C80	0.906 (4M)	0.905 (W24)	-	-	-
D	-0.808 (W24)	-0.809 (W24)	0.969 (ALL)	-	-
TS	0.994 (4M)	0.996 (4M)	-0.925 (4M)	0.838 (W24)	-
L	-0.407 (O24)	-0.397 (O24)	0.445 (4H)	0.431 (2F)	0.397 (O24)

TABLE E.2 - Number of best fits achieved using each of the seven averaging options.

AVERAGING OPTION	BEST FITS
ALL - Average of all 6 frequencies (125 to 4000 Hz octave bands)	2
W24 - Average of the 4 lowest frequencies (125 to 1000 Hz octave bands)	4
4H - Average of the 4 highest frequencies (500 to 4000 Hz octave bands)	1
2F - Average of 2 medium frequencies (500 and 1000 Hz octave bands)	1
O24 - Average of the 2 highest frequencies (2000 and 4000 Hz octave bands)	3
3F - Average of 3 medium frequencies (500 Hz, 1 and 2 kHz octave bands)	0
4M - Average of 4 middle frequencies (250 to 2000 Hz octave bands)	4

TABLE E.3 - Squared linear correlation coefficients among acoustical measures using the seven options of averaging. The highest values in each row are bold faced if $R^2 > 0.60$.

R^2	ALL FREQ.	4 HIGHEST	4 LOWEST	500/1k	500/1k/2k	4 MIDDLE	2k/4k
RT-EDT	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	0.99
RT-C80	0.80	0.79	**0.82**	0.81	0.80	**0.82**	0.74
RT-D	0.64	0.59	**0.65**	0.59	0.59	0.64	0.57
RT-TS	**0.99**	**0.99**	**0.99**	0.98	**0.99**	**0.99**	0.98
RT-L	0.07	0.13	0.04	0.09	0.11	0.08	0.17
RT-BR.RT	0.08	0.02	0.12	0.04	0.03	0.06	0.01
RT-BR.L	0.00	0.01	0.00	0.01	0.01	0.00	0.02
EDT-C80	0.81	0.80	**0.82**	0.81	0.81	**0.82**	0.78
EDT-D	**0.65**	0.60	**0.65**	0.59	0.60	0.64	0.61
EDT-TS	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**
EDT-L	0.07	0.12	0.03	0.08	0.10	0.07	0.16
EDT-BR.RT	0.09	0.02	0.13	0.04	0.03	0.07	0.01
EDT-BR.L	0.00	0.01	0.00	0.01	0.01	0.01	0.02
C80-D	**0.94**	0.92	**0.94**	0.91	0.92	0.93	0.93
C80-TS	0.85	0.85	0.85	0.85	0.85	**0.86**	0.84
C80-L	0.11	0.20	0.06	0.19	0.19	0.15	0.17
C80-BR.RT	0.08	0.02	0.13	0.03	0.02	0.06	0.01
C80-BR.L	0.01	0.02	0.00	0.02	0.02	0.01	0.03
D-TS	**0.70**	0.66	**0.70**	0.64	0.66	0.69	0.68
D-L	0.06	0.16	0.03	0.19	0.16	0.12	0.11
D-BR.RT	0.09	0.02	0.15	0.02	0.02	0.06	0.01
D-BR.L	0.00	0.03	0.00	0.03	0.03	0.01	0.02
TS-L	0.07	0.14	0.04	0.10	0.12	0.08	0.16
TS-BR.RT	0.09	0.03	0.13	0.04	0.03	0.06	0.01
TS-BR.L	0.00	0.01	0.00	0.01	0.01	0.00	0.01
L-BR.RT	0.19	0.16	0.23	0.20	0.18	0.20	0.13
L-BR.L	0.25	0.19	0.29	0.19	0.19	0.22	0.18
BR.RT-BR.L	0.23	0.23	0.23	0.23	0.23	0.23	0.23
TOTAL OF CASES	6	3	9	2	3	6	1

APPENDIX F
BASS RATIOS

TABLE F.1 - List of bass ratios results for the 41 churches tested.

	CHURCH	BR_RT	BR_L		CHURCH	BR_RT	BR_L
1	ALMANSIL	0.99	2.53	22	S. CLARA porto	0.75	1.21
2	ARMAMAR	0.88	0.95	23	S. B. CASTRIS	1.11	2.39
3	BAS. ESTRELA lisboa	1.02	1.92	24	S. FRAN. évora	0.94	-0.10
4	BRAVÃES	1.07	2.38	25	S. FRAN. porto	0.85	0.35
5	BUSTELO	0.86	0.43	26	S. FRUTUOSO	1.07	2.63
6	CABEÇA SANTA	0.96	1.55	27	S. GENS	1.34	2.85
7	CAMINHA	0.75	0.68	28	S. P. FERREIRA	1.02	2.13
8	CEDOFEITA.new porto	1.25	1.60	29	S. P. RATES	1.02	1.36
9	CEDOFEITA.old porto	1.28	1.58	30	RORIZ	0.93	3.30
10	CETE	1.00	1.61	31	S.ROQUE lisboa	0.80	0.57
11	CLÉRIGOS porto	1.15	2.40	32	SÉ lamego	0.81	1.23
12	GOLEGÃ	0.72	1.01	33	SÉ porto	1.08	1.61
13	LAPA porto	0.94	1.65	34	SILVES	0.95	0.46
14	LEÇA DO BAILIO	0.90	1.60	35	SERÔA	1.06	2.39
15	LOUROSA	0.85	1.26	36	S. PILAR gaia	1.04	1.19
16	MÉRTOLA	1.39	2.08	37	TIBÃES	0.88	1.31
17	MISERICÓRDIA évora	0.84	0.35	38	V. ALENTEJO	1.04	1.21
18	MOURA	1.25	2.08	39	VILA BISPO	0.86	-0.40
19	N. S. BOAVISTA porto	1.30	1.91	40	V. N. AZEITÃO	0.72	0.87
20	PAÇO SOUSA	0.91	1.11	41	VOUZELA	0.92	4.21
21	SANT. SACR. porto	0.91	1.04				

APPENDIX G
SOUND SOURCE POSITION ANALYSIS (*T*-TEST)

TABLE G.1 - Probability-values of a two-sample *t* test comparing acoustical measures by sound source position (Altar vs. Congregation). The p-values < 0.05, indicating significant differences between sound source positions, are shown in bold face.

Two-sample *t* test - Prob. values (*ALTAR* vs *CONGREGATION* sound source positions)						
Church	RT	EDT	C80	D	TS	L
1	0.835	0.090	0.865	0.810	0.583	0.436
2	0.550	0.949	0.926	0.964	0.935	0.520
3	0.629	0.063	**0.029**	0.116	0.053	0.073
4	0.575	0.976	**0.028**	0.117	0.069	0.001
5	0.766	0.337	**0.025**	**0.004**	**0.013**	**0.000**
6	0.338	0.403	0.336	0.718	0.388	0.028
7	0.903	0.589	**0.003**	**0.000**	**0.012**	**0.000**
8	0.600	0.693	**0.000**	**0.006**	0.105	0.233
9	0.775	0.841	0.385	0.048	0.828	0.137
10	0.897	0.216	0.730	0.674	0.254	0.133
11	0.310	0.101	0.545	0.926	0.214	**0.002**
12	0.852	0.369	**0.039**	**0.022**	**0.017**	**0.006**
13	0.699	0.604	0.105	0.028	0.723	0.192
14	0.573	0.561	**0.008**	**0.025**	0.333	0.488
15	0.173	**0.000**	**0.000**	**0.000**	**0.000**	**0.004**
16	0.688	0.970	0.223	0.131	0.849	0.429
17	0.334	0.839	**0.001**	**0.000**	**0.001**	**0.000**
18	0.663	0.867	0.526	0.810	0.864	0.093
19	0.896	0.834	0.702	0.769	0.602	0.168
20	0.454	0.227	0.178	0.212	0.055	**0.000**
21	0.969	0.612	0.258	0.697	0.276	**0.031**
22	0.977	0.665	0.829	0.838	0.728	**0.022**
23	0.751	0.611	0.777	0.700	0.695	0.840
24	0.132	0.597	**0.002**	**0.002**	**0.041**	**0.000**
25	0.579	0.827	0.370	0.094	0.335	**0.042**
26	0.823	0.417	0.236	0.171	0.114	0.097
27	0.422	0.282	**0.045**	0.103	0.100	0.132
28	0.803	0.375	0.070	0.245	0.442	0.812
29	0.897	0.184	**0.007**	**0.001**	**0.001**	**0.008**
30	0.881	0.157	**0.034**	**0.022**	**0.003**	0.316
31	0.342	0.929	**0.004**	**0.000**	**0.011**	**0.001**
32	**0.017**	**0.000**	**0.000**	**0.025**	**0.000**	**0.000**
33	0.664	0.344	0.768	0.229	0.912	**0.000**
34	0.510	0.064	**0.008**	**0.023**	**0.000**	**0.014**
35	0.814	0.957	0.857	0.472	0.541	0.677
36	0.991	0.993	0.580	0.340	0.990	0.059
37	0.647	0.131	**0.003**	**0.001**	**0.001**	**0.000**
38	0.973	0.809	0.855	1.000	0.927	0.264
39	0.356	0.598	0.625	0.319	0.347	**0.012**
40	0.703	0.832	**0.028**	**0.023**	0.060	**0.000**
41	0.475	0.595	0.421	0.704	0.208	**0.004**

APPENDIX H
EFFECT OF ARCHITECTURAL STYLES ON ACOUSTICAL MEASURES VALUES

TABLE H.1 - Matrix of ANOVA pairwise comparison probabilities regarding architectural styles (averaged data). P. < 0.05 indicates a significant difference between the two means for the pair of styles analyzed.

Acous. Param.	Arc. Styl.	ARCHIT. STYLES 1	2	3	4	5	6	7
RT	2	0.603	-	-	-	-	-	-
	3	0.474	0.999	-	-	-	-	-
	4	0.008	0.021	0.223	-	-	-	-
	5	0.000	0.001	0.003	0.079	-	-	-
	6	0.824	0.998	0.962	0.006	0.000	-	-
	7	0.000	0.000	0.001	0.094	0.996	0.000	-
	8	0.033	0.177	0.586	1.000	0.057	0.070	0.067
EDT	2	0.574	-	-	-	-	-	-
	3	0.399	0.997	-	-	-	-	-
	4	0.006	0.016	0.229	-	-	-	-
	5	0.000	0.001	0.003	0.083	-	-	-
	6	0.813	0.997	0.922	0.004	0.000	-	-
	7	0.000	0.000	0.002	0.160	0.988	0.000	-
	8	0.029	0.172	0.643	1.000	0.054	0.063	0.101
C80	2	0.238	-	-	-	-	-	-
	3	0.104	0.975	-	-	-	-	-
	4	0.007	0.169	0.864	-	-	-	-
	5	0.030	0.368	0.726	0.985	-	-	-
	6	0.659	0.901	0.513	0.016	0.146	-	-
	7	0.005	0.095	0.446	0.948	1.000	0.018	-
	8	0.025	0.531	0.983	1.000	0.962	0.114	0.890
D	2	0.345	-	-	-	-	-	-
	3	0.177	0.986	-	-	-	-	-
	4	0.036	0.500	0.985	-	-	-	-
	5	0.169	0.821	0.977	1.000	-	-	-
	6	0.887	0.720	0.388	0.038	0.411	-	-
	7	0.079	0.696	0.974	1.000	1.000	0.192	-
	8	0.097	0.859	1.000	1.000	0.998	0.199	0.999
TS	2	0.563	-	-	-	-	-	-
	3	0.352	0.993	-	-	-	-	-
	4	0.007	0.021	0.318	-	-	-	-
	5	0.000	0.001	0.003	0.074	-	-	-
	6	0.875	0.978	0.786	0.003	0.000	-	-
	7	0.000	0.001	0.006	0.235	0.965	0.000	-
	8	0.035	0.222	0.767	0.999	0.046	0.055	0.143
L	2	0.983	-	-	-	-	-	-
	3	0.677	0.865	-	-	-	-	-
	4	0.795	0.961	1.000	-	-	-	-
	5	0.946	0.998	1.000	1.000	-	-	-
	6	0.578	0.673	1.000	1.000	1.000	-	-
	7	0.453	0.632	0.994	0.967	0.999	0.992	-
	8	0.846	0.984	1.000	1.000	1.000	1.000	0.974

APPENDIX I
RESULTS FOR THE FIFTEEN ARCHITECTURAL PARAMETERS IN ALL CHURCHES

TABLE I.1 - General analysis for the fifteen architectural styles in all churches.

	CHURCH	VOL. total (m^3)	VOL. nave (m^3)	ARE. total (m^2)	ARE. nave (m^2)	L. max (m)	L. nave (m)	H. max (m)	Hnav e,avg (m)	W. nave (m)	W. avg (m)	V.tot/ A.tot (m)	Seats	Abso Total (m^2)	R local (m^2)	alpha. avg
1	ALMANSIL	578	372	91	64	15.3	10.7	8.0	5.8	6.0	6.0	6.4	64	24	26	0.051
2	ARMAMAR	2487	2241	260	226	26.9	21.0	10.8	9.9	10.8	10.8	9.6	130	66	69	0.054
3	ESTRELA	18674	15936	823	693	49.7	40.0	39.0	23.0	11.0	17.8	22.7	623	191	199	0.039
4	BRAVÃES	946	773	111	83	19.7	12.8	10.2	9.3	6.4	6.4	8.5	26	31	32	0.048
5	BUSTELO	6476	5166	515	401	46.0	32.2	16.1	14.9	10.5	12.6	12.6	421	226	249	0.091
6	CAB.SANTA	751	558	108	69	17.9	11.6	8.7	8.1	5.9	5.9	7.0	80	40	43	0.070
7	CAMINHA	5899	4706	641	502	40.9	33.3	14.4	9.4	15.4	15.4	9.2	252	228	249	0.085
8	CED. new pt	8470	6578	966	781	34.3	28.6	13.4	8.6	25.7	28.8	8.8	547	341	379	0.101
9	CED. old pt	1117	922	126	92	23.0	15.6	10.7	10.0	5.9	5.9	8.9	80	21	21	0.030
10	CETE	1515	1201	155	110	28.7	20.2	11.8	10.9	5.4	5.4	9.8	136	50	53	0.054
11	CLÉRIGOS pt	5130	4032	273	212	33.9	23.5	20.0	19.0	10.7	9.5	18.8	169	112	119	0.061
12	GOLEGÃ	5563	4873	545	473	40.4	30.1	13.7	10.3	15.7	15.7	10.2	384	131	138	0.055
13	LAPA porto	11423	8787	753	542	52.5	36.4	17.0	16.2	14.9	14.9	15.2	468	328	355	0.076
14	LEÇA	9795	9112	611	539	41.1	33.7	19.1	16.9	16.0	16.0	16.0	318	170	178	0.045
15	LOUROSA	1163	1040	197	164	18.5	12.9	8.5	6.8	10.8	12.7	5.9	63	47	50	0.056
16	MÉRTOLA	1950	1950	297	297	15.9	15.9	7.2	6.6	18.6	18.6	6.6	148	62	65	0.046
17	MISERIC. év	3338	2810	250	207	26.2	21.3	14.7	13.6	9.7	9.7	13.4	92	163	184	0.115
18	MOURA	6300	5705	611	519	40.7	31.0	13.4	11.0	16.8	16.8	10.3	250	131	136	0.039
19	BOAVISTA	3740	3108	499	406	23.4	16.8	7.9	7.7	26.1	24.2	7.5	428	152	165	0.083
20	P. SOUSA	6028	4564	546	397	43.0	25.1	16.8	11.5	15.9	15.9	11.0	198	119	125	0.047
21	S. SACR. pt	6816	4894	510	333	40.7	26.8	15.5	14.7	13.0	13.0	13.4	220	233	255	0.085
22	S. CLARA pt	2491	2022	222	173	26.7	18.6	12.9	11.7	9.4	9.4	11.2	190	236	307	0.230
23	S.B.CASTRIS	1314	978	130	93	23.2	15.0	13.0	10.9	6.7	8.5	10.1	136	76	82	0.077
24	S. FRAN. év	18631	14246	1031	673	54.5	41.6	25.1	21.2	12.7	16.4	18.1	385	351	370	0.052
25	S. FRAN. po	12045	11120	813	735	46.8	40.7	18.0	15.1	18.2	19.4	14.8	496	962	1222	0.213
26	S.FRUTUOS	320	271	56	46	11.5	8.5	9.4	5.9	3.6	5.7	5.7	0	22	24	0.063
27	S. GENS	299	250	56	42	13.3	8.3	6.5	6.0	5.0	5.0	5.3	0	14	14	0.048
28	FERREIRA	2912	2301	233	169	29.4	19.3	14.5	13.6	8.7	8.7	12.5	116	72	76	0.055
29	S. P. RATES	3918	3386	427	364	31.5	22.7	12.9	9.3	16.0	16.0	9.2	265	94	98	0.044
30	RORIZ	2198	1879	193	153	28.3	20.1	13.3	12.3	7.6	7.6	11.4	198	58	61	0.058
31	S. ROQUE lx	14207	12534	929	753	43.6	40.8	17.1	16.7	17.4	18.5	15.3	210	441	489	0.098
32	SÉ lamego	13424	10473	968	741	57.8	37.8	22.2	14.1	17.5	19.2	13.9	323	302	322	0.062
33	SÉ porto	15260	11232	982	711	62.2	42.3	22.3	15.8	15.0	17.6	15.5	490	261	273	0.047
34	SILVES	10057	8628	746	583	41.9	31.8	16.7	14.8	17.0	18.3	13.5	258	228	241	0.057
35	SEROA	4225	4225	635	635	19.0	19.0	17.0	6.7	37.5	36.8	6.7	480	159	173	0.081
36	S. PILAR	11566	10400	591	408	37.2	26.0	35.1	26.0	22.8	20.2	19.6	272	228	245	0.069
37	TIBÃES	8608	5416	595	322	47.0	30.3	19.3	16.8	9.4	10.4	14.5	252	259	279	0.073
38	V.ALENTEJO	3358	3160	421	378	30.8	27.3	11.0	8.4	14.8	14.8	8.0	226	120	129	0.066
39	V. BISPO	1290	950	220	153	28.8	20.8	6.9	6.2	7.6	7.6	5.9	140	98	109	0.103
40	AZEITAO	1239	975	174	125	24.9	16.4	8.2	7.8	7.9	7.9	7.1	144	65	70	0.080
41	VOUZELA	1148	870	150	102	22.0	15.5	9.2	8.5	6.6	6.6	7.7	163	63	68	0.082

APPENDIX J
THE SEARCH FOR A REPRESENTATIVE SINGLE NUMBER AVERAGE FOR RELATIONSHIPS BETWEEN ACOUSTICAL MEASURES AND ARCHITECTURAL PARAMETERS

Using each of the seven frequency-averaging options stated earlier (Table 3.4), linear regression models were determined for each of the eight acoustical measures regarding their relationships with the fifteen architectural parameters considered individually or with general linear models.

Table J.1 presents a summary of the results of the relationships using only one architectural parameters with two decimal places in order to dissipate the small and insignificant differences among R values. For each of the eight acoustical measures, seven R values are displayed, each one being the maximum obtained with a linear regression with the fifteen architectural parameters. For example, the acoustical measure RT has its maximum R using the 41_4H, 41_2F, 41_O24 or 41_3F options. In Table J.1 it is clearly shown that the best option is the 41_2F (using only 500 and 1000 Hz bands). Nevertheless, the differences regarding the other cases are not great ($\Delta R \leq 0.10$). The worst option seems to be the 41_W24 (using the 4 lowest frequency bands) with 0.07 smaller R's on average than the best option (the 41_2F). These results support the idea to only use the average of the data in the 500 and 1000 Hz octave frequency bands in the analyses.

Table J.2 presents the summary results of the maximum R values determined for each acoustical measure and for each of the seven options of frequency-averaging using general linear models (more than one architectural parameter). In each column (each acoustical measure) the highest value is shaded. Table J.2 shows the results with two decimal places in

TABLE J.1 - Maximum Pearson regression coefficients (relationships between acoustical measures and one architectural parameter). The highest R values in each column are shaded.

Frequencies	code	RT	EDT	C80	D	TS	L	BR_RT	BR_L
ALL	41_ALL	0.69	0.68	0.60	0.53	0.68	0.88		
4 LOWEST	41_W24	0.67	0.66	0.58	0.54	0.66	0.88		
4 HIGHEST	41_4H	**0.74**	**0.73**	0.64	0.56	**0.74**	0.88		
500 - 1k	41_2F	**0.74**	**0.73**	**0.68**	**0.61**	**0.74**	0.87	0.38	0.50
2 - 4k	41_O24	**0.74**	0.72	0.59	0.51	0.71	**0.89**		
500 to 2k	41_3F	**0.74**	**0.73**	0.66	0.57	0.74	0.88		
4 MIDDLE	41_4M	0.72	0.71	0.65	0.57	0.71	0.88		

order to dissipate the small and non significant differences among R values. In Table J.2 it is clearly shown that the best option is the 41_2F (using only 500 and 1k Hz bands).

Nevertheless, the differences to the other cases are not great ($\Delta R \leq 0.09$). The option with the lowest R value is the 41_W24 (using the 4 lowest frequency bands) with 0.03 smaller Rs on average than the best option. These results also support, the use of only the 500 and 1k Hz octave frequency bands in the analyses.

TABLE J.2 - Maximum Pearson regression coefficients of general linear models with the architectural parameters. The highest R values in each column are shaded.

Frequencies	code	RT	EDT	C80	D	TS	L	BR_RT	BR_L
ALL	41_ALL	0.82	0.82	0.90	0.90	0.84	**0.94**		
4 LOWEST	41_W24	0.81	0.81	0.90	0.87	0.83	0.92		
4 HIGHEST	41_4H	**0.85**	**0.84**	0.91	0.90	**0.86**	0.91		
500 and 1k	41_2F	**0.85**	**0.84**	**0.92**	**0.91**	**0.86**	**0.94**	0.59	0.50
2 and 4 k	41_O24	0.83	0.83	0.87	0.83	0.84	0.91		
500 to 2k	41_3F	**0.85**	**0.84**	0.91	**0.91**	**0.86**	0.91		
4 MIDDLE	41_4M	0.84	0.83	0.91	0.89	0.85	0.91		

APPENDIX K
GENERAL LINEAR MODEL COEFFICIENTS

TABLE K.1 - Standard errors and standardized coefficients for all the general linear model predictors regarding the relationships between acoustical mesures and architectural parameters (see Table 4.7).

ACOUSTICAL MEASURE	VARIABLE	COEFFICIENT	STD ERROR	STD COEF.
RT	Constant	1.148	0.470	0.000
	H_MAX	0.149	0.022	0.624
	W_NAVE	0.078	0.022	0.323
	ALPHA	-13.383	3.691	-0.322
EDT	Constant	1.075	0.466	0.000
	H_MAX	0.145	0.022	0.620
	W_NAVE	0.077	0.022	0.327
	ALPHA	-12.756	3.660	-0.313
C80	Constant	0.864	0.667	0.000
	W_NAVE	-0.217	0.028	-0.510
	VTO_ATO	-0.404	0.044	-0.592
	ALPHA	35.121	4.767	0.477
D	Constant	0.452	0.038	0.000
	VOL_TOT	0.000014	0.000	0.846
	L_NAVE	-0.007	0.002	-0.748
	W_NAVE	-0.008	0.001	-0.549
	VTO_ATO	-0.014	0.003	-0.637
	ALPHA	1.364	0.174	0.556
TS	Constant	85.448	31.656	0.000
	H_MAX	10.603	1.489	0.623
	W_NAVE	5.941	1.503	0.348
	ALPHA	-983.356	248.822	-0.332
L	Constant	22.918	0.758	0.000
	L_NAVE	-0.306	0.025	-0.837
	ALPHA	-24.520	6.250	-0.268
BR_RT	Constant	1.280	0.074	0.000
	SEATS	0.00045	0.000	0.465
	L_MAX	-0.008	0.002	-0.638
	ALPHA	-1.883	0.581	-0.436
BR_L	Constant	2.663	0.340	0.000
	L_NAVE	-0.047	0.013	-0.500

STD ERROR - Standard errors for the coefficients of the regression models. This shows how much to expect the coefficients to vary if they are computed from new samples.

STD COEF. - Standardized coefficients for the regression models. These values are used to interpret the relative contributions of the predictors because they have comparable magnitude.

APPENDIX L
DATA REGARDING THE USE OF THE SABINE AND EYRING EQUATIONS

This Appendix presents the results of the application of the Sabine and Eyring equations to this ample of churches. Table L.1 shows the absorption coefficients (α) used. Table L.2 presents the results concerning the direct application of these two equations to the 41 churches measured. The effect of coupled spaces such as chapels, apses, etc. were not considered in the calculation. For each church, two RT values are given using Volume Total (VT) and Volume Nave (VN) in the prediction equation. Nave stands for the area of the church excluding the lateral chapels and the main altar/apse. For both the Sabine and Eyring equations, there are two columns in the Table where the differences between the RT measured in loco and the expected RT calculated by the Sabine or Eyring equations are computed. The average of those 41 differences (AVGabs) calculated using the absolute value of each individual difference are shown at the bottom of each of the difference columns (Diff.). Table L.3 presents the final results of the application of the Sabine equation using an $\alpha = 0.9$ in all openings to chapels or to the main altar area. As seen in Table L.3, this approach still does not give reasonable results (note that in this case, the Differences regarding the Volume of the Nave is the column to look to). Table L.4 displays the results of the application of the Sabine equation including the coupled spaces algorithm. In the column ABS(diff)%, the absolute differences (in percentage) of the RT_{SABINE} vs. RT_{REAL} are shown.

TABLE L.1 - Sound absorption coefficients for f = 500 & 1000 Hz used in the reverberation time calculations.

VOLUME	AIR	0.0015	CEILINGS	stone w/ boxes	0.02
WALLS	canvas	0.23		concrete w/ large boxes	0.075
	wood	0.13		plaster	0.05
	wood w/ air space	0.09		plaster w/ boxes	0.09
	wood carving	0.30		wood - plain	0.10
	plaster on brick/stone	0.025		wood - w/ beamlets	0.13
	glazed tiles	0.01		wood w/ boxes	0.20
	concrete	0.02		wood Mudejar	0.18
	stone (granite)	0.01		acoustic ceiling	0.40
	stone (limestone)	0.01		concrete w/ small shapes	0.025
	stained glass	0.10	GENERAL	openings	0.90
	marble	0.01	ABSORPTION-m3	statues (wood ref. 0.5m)	0.80
	plastic	0.28		pews (normal-light wood)	0.04
FLOORS	carpet - light	0.15		pews (heavy wood/little cush.)	0.10
	carpet - heavy	0.35		pews (cushioned)	0.17
	wood	0.10		windscreen/doors (ref. 20 m2)	2
	wood w/ air space	0.12		draperies heavy (ref. big door)	2.3
	stone	0.03		person	0.46
	concrete	0.02		altar, organ, conf.box,etc (each)	1
	wood caissons - tombs	0.10			
	marble(altars)	0.02			
	terrazzo	0.02			

Sources: (Wilson 1989; Silva 1978; Egan 1988)

TABLE L.2 - Calculation of RT using the Sabine (sab) and Eyring (eyr) equations with no coupled spaces effect considered. Differences in % using total volume (VT) or the volume of the nave (VN) in the calculations.

CHURCH	RTsab.VT (s)	RTsab.VN (s)	RTreal (s)	Diff.-VT (%)	Diff.-VN (%)	RTeyr.VT (s)	RTeyr.VN (s)	Diff.-VT (%)	Diff.-VN (%)
1 ALMANSIL	3.79	2.44	2.03	86	20	3.57	2.30	76	13
2 ARMAMAR	6.08	5.48	2.57	137	113	5.60	5.05	118	97
3 ESTRELA	15.63	13.34	8.14	92	64	13.40	11.44	65	40
4 BRAVÃES	4.95	4.04	1.88	163	115	4.62	3.78	145	101
5 BUSTELO	4.59	3.66	4.07	13	-10	4.20	3.35	3	-18
6 CAB. SANTA	2.98	2.21	1.79	67	24	2.79	2.08	56	16
7 CAMINHA	4.15	3.31	2.85	45	16	3.82	3.05	34	7
8 CED. new	3.98	3.09	3.09	29	0	3.64	2.83	18	-8
9 CED. old	8.69	7.18	3.62	140	98	7.93	6.54	119	81
10 CETE	4.86	3.85	2.28	113	69	4.53	3.59	99	57
11 CLÉRIGOS	7.32	5.76	3.35	119	72	6.66	5.23	99	56
12 GOLEGÃ	6.82	5.98	3.62	88	65	6.24	5.47	72	51
13 LAPA	5.57	4.29	5.72	-3	-25	5.10	3.93	-11	-31
14 LEÇA	9.23	8.59	4.37	111	96	8.32	7.74	90	77
15 LOUROSA	3.97	3.55	1.60	148	122	3.72	3.33	133	108
16 MÉRTOLA	5.04	5.04	4.56	11	11	4.71	4.71	3	3
17 MISERIC. évo	3.27	2.75	2.26	45	22	2.99	2.52	32	11
18 MOURA	7.71	6.98	6.57	17	6	7.06	6.39	8	-3
19 BOAVISTA	3.95	3.28	3.98	-1	-18	3.65	3.03	-8	-24
20 P. SOUSA	8.13	6.15	2.94	177	109	7.39	5.59	151	90
21 S. SACR.	4.67	3.36	5.02	-7	-33	4.29	3.08	-14	-39
22 S. CLARA	1.69	1.37	1.25	35	10	1.46	1.19	17	-5
23 S. B. CASTRIS	2.77	2.07	3.14	-12	-34	2.60	1.94	-17	-38
24 S. FRAN. évo	8.50	6.50	5.04	69	29	7.68	5.88	52	17
25 S. FRAN. por	2.00	1.85	1.78	12	4	1.75	1.62	-2	-9
26 S. FRUTUOSO	2.29	1.94	1.20	92	62	2.18	1.84	82	54
27 S. GENS	3.48	2.91	1.53	127	90	3.29	2.75	115	80
28 FERREIRA	6.45	5.10	3.28	97	55	5.92	4.68	81	43
29 RATES	6.66	5.76	3.00	122	92	6.14	5.30	104	77
30 RORIZ	6.07	5.19	3.01	102	72	5.59	4.78	85	59
31 S. ROQUE	5.15	4.55	3.77	37	21	4.68	4.13	24	10
32 SÉ lamego	7.12	5.55	4.55	56	22	6.48	5.05	42	11
33 SÉ porto	9.37	6.90	3.59	161	92	8.43	6.20	134	73
34 SILVES	7.07	6.07	3.93	80	54	6.46	5.54	64	41
35 SEROA	4.26	4.26	4.57	-7	-7	3.94	3.94	-14	-14
36 S. PILAR	8.12	7.30	7.83	4	-7	7.30	6.56	-7	-16
37 TIBÃES	5.32	3.35	2.72	96	23	4.89	3.08	80	13
38 V. ALENTEJO	4.47	4.21	3.05	47	38	4.16	3.91	36	28
39 V. BISPO	2.11	1.56	1.78	19	-13	1.96	1.45	10	-19
40 V.N.AZEITÃO	3.06	2.41	2.31	32	4	2.86	2.25	24	-3
41 VOUZELA	2.93	2.22	1.45	102	53	2.73	2.07	89	43
			AVGabs	**71**	**46**		**AVGabs**	**59**	**39**

TABLE L.3 - Calculation of RT using the Sabine (sab) and Eyring (eyr) equations with coupled spaces effect considered with $\alpha = 0.9$ in all recesses. Differences in % using total volume (VT) or the volume of the nave (VN) in the calculations.

	CHURCH	RTsab.VT (s)	RTsab.VN (s)	RTreal (s)	Diff.-VT (%)	Diff.-VN (%)	RTeyr.VT (s)	RTeyr.VN (s)	Diff.-VT (%)	Diff.-VN (%)
1	ALMANSIL	3.79	2.44	2.03	86	20	3.57	2.30	76	13
2	ARMAMAR	4.18	3.77	2.57	63	47	3.87	3.49	51	36
3	BAS. ESTRELA	7.84	6.69	8.14	-4	-18	7.04	6.01	-14	-26
4	BRAVÃES	3.66	2.99	1.88	94	59	3.42	2.80	82	49
5	BUSTELO	3.37	2.69	4.07	-17	-34	3.06	2.44	-25	-40
6	CAB. SANTA	1.91	1.42	1.79	7	-21	1.77	1.32	-1	-26
7	CAMINHA	2.57	2.05	2.85	-10	-28	2.34	1.86	-18	-35
8	CED. new porto	3.52	2.73	3.09	14	-11	3.22	2.50	4	-19
9	CED. old porto	4.86	4.01	3.62	34	11	4.53	3.74	25	3
10	CETE	2.95	2.34	2.28	29	2	2.74	2.17	20	-5
11	CLÉRIGOS pt	4.29	3.37	3.35	28	1	3.91	3.08	17	-8
12	GOLEGÃ	2.73	2.39	3.62	-25	-34	2.48	2.17	-32	-40
13	LAPA porto	3.84	2.96	5.72	-33	-48	3.51	2.70	-39	-53
14	LEÇA	6.34	5.90	4.37	45	35	5.80	5.39	33	23
15	LOUROSA	3.08	2.76	1.60	93	72	2.89	2.58	81	61
16	MÉRTOLA	5.04	5.04	4.56	11	11	4.71	4.71	3	3
17	MISERIC évora	3.27	2.75	2.26	45	22	2.99	2.52	32	11
18	MOURA	4.72	4.27	6.57	-28	-35	4.38	3.97	-33	-40
19	BOAVISTA	2.18	1.81	3.98	-45	-54	1.98	1.64	-50	-59
20	PAÇO SOUSA	5.83	4.41	2.94	98	50	5.35	4.05	82	38
21	S. SACR. porto	3.32	2.38	5.02	-34	-53	3.03	2.17	-40	-57
22	S. CLARA pt	1.43	1.16	1.25	15	-7	1.21	0.98	-3	-21
23	S. B. CASTRIS	2.77	2.07	3.14	-12	-34	2.60	1.94	-17	-38
24	S. FRAN. évora	3.25	2.49	5.04	-36	-51	2.94	2.25	-42	-55
25	S. FRAN. porto	1.76	1.62	1.78	-1	-9	1.51	1.40	-15	-22
26	S. FRUTUOSO	2.29	1.94	1.20	92	62	2.18	1.84	82	54
27	S. GENS	2.58	2.16	1.53	69	41	2.44	2.04	59	33
28	FERREIRA	4.10	3.24	3.28	25	-1	3.78	2.99	15	-9
29	RATES	3.84	3.31	3.00	28	10	3.56	3.08	19	3
30	RORIZ	3.89	3.33	3.01	29	11	3.59	3.07	19	2
31	S. ROQUE	2.63	2.32	3.77	-30	-38	2.31	2.04	-39	-46
32	SÉ lamego	5.51	4.30	4.55	21	-6	5.03	3.93	11	-14
33	SE porto	6.29	4.63	3.59	75	29	5.74	4.22	60	18
34	SILVES	4.58	3.93	3.93	16	0	4.20	3.60	7	-8
35	SEROA	4.26	4.26	4.57	-7	-7	3.94	3.94	-14	-14
36	S. PILAR gaia	3.45	3.10	7.83	-56	-60	3.07	2.76	-61	-65
37	TIBÃES	2.79	1.76	2.72	3	-35	2.53	1.59	-7	-42
38	V. ALENTEJO	3.22	3.03	3.05	6	-1	2.98	2.81	-2	-8
39	V. BISPO	1.53	1.13	1.78	-14	-37	1.40	1.03	-21	-42
40	V. N. AZEITÃO	2.23	1.75	2.31	-4	-24	2.06	1.62	-11	-30
41	VOUZELA	2.30	1.74	1.45	59	20	2.13	1.62	47	12
				AVGabs	35	28		AVGabs	32	29

TABLE L.4 - Calculation of RT using the Sabine (sab) equation with the coupled spaces effect considered (proposed algorithm). Differences in % using the final volume (VF) in the calculations.

	CHURCH	Vol.type	RTsab.VF (s)	RTreal (s)	Diff.VF (%)	ABS(diff) (%)	Diff. (s)	ABS(diff) (s)
1	ALMANSIL	V.nave	1.63	2.03	-20	20	-0.4	0.4
2	ARMAMAR	V.nave	4.26	2.57	66	66	1.7	1.7
3	BAS. ESTRELA lisboa	V.nave	8.07	8.14	-1	1	-0.1	0.1
4	BRAVÃES	V.nave	2.93	1.88	56	56	1.0	1.0
5	BUSTELO	Vt-Vtr	4.17	4.07	3	3	0.1	0.1
6	CABEÇA SANTA	V.nave	1.72	1.79	-4	4	-0.1	0.1
7	CAMINHA	V.nave	2.84	2.85	0	0	0.0	0.0
8	CEDOFEITA new porto	Vt-Vch.	3.92	3.09	27	27	0.8	0.8
9	CEDOFEITA old porto	V.nave	3.95	3.62	9	9	0.3	0.3
10	CETE	V.nave	2.47	2.28	9	9	0.2	0.2
11	CLÉRIGOS porto	V.nave	3.38	3.35	1	1	0.0	0.0
12	GOLEGÃ	V.nave	2.11	3.62	-42	42	-1.5	1.5
13	LAPA porto	V.Total	5.57	5.72	-3	3	-0.1	0.1
14	LEÇA	V.nave	4.87	4.37	11	11	0.5	0.5
15	LOUROSA	Vnave-Vla	1.81	1.60	13	13	0.2	0.2
16	MÉRTOLA	V.Total	5.04	4.56	11	11	0.5	0.5
17	MISERICÓRDIA évora	V.Total	3.27	2.26	45	45	1.0	1.0
18	MOURA	V.nave	3.88	6.57	-41	41	-2.7	2.7
19	N. S. BOAVISTA porto	V.Total	3.95	3.98	-1	1	0.0	0.0
20	PAÇO SOUSA	V.nave	2.88	2.94	-2	2	-0.1	0.1
21	SANT. SACRAM. porto	V.Total	4.67	5.02	-7	7	-0.3	0.3
22	S. CLARA porto	V.Total	1.69	1.25	35	35	0.4	0.4
23	S. B. CASTRIS	V.Total	2.77	3.14	-12	12	-0.4	0.4
24	S. FRANCISCO évora	V.nave	4.91	5.04	-3	3	-0.1	0.1
25	S. FRANCISCO porto	V.nave	1.64	1.78	-8	8	-0.1	0.1
26	S. FRUTUOSO	V.nave	1.51	1.20	26	26	0.3	0.3
27	S. GENS	V.nave	0.99	1.53	-35	35	-0.5	0.5
28	S. P. FERREIRA	V.nave	3.28	3.28	0	0	0.0	0.0
29	S. P. RATES	V.nave	3.37	3.00	12	12	0.4	0.4
30	RORIZ	V.nave	3.39	3.01	12	12	0.4	0.4
31	S. ROQUE lisboa	V.nave	4.50	3.77	19	19	0.7	0.7
32	SÉ lamego	V.nave	4.29	4.55	-6	6	-0.3	0.3
33	SÉ porto	V.nave	4.54	3.59	26	26	0.9	0.9
34	SILVES	V.nave	3.94	3.93	0	0	0.0	0.0
35	SEROA	V.Total	4.26	4.57	-7	7	-0.3	0.3
36	SERRA PILAR gaia	Vt-Vma	5.95	7.83	-24	24	-1.9	1.9
37	TIBÃES	V.nave	2.53	2.72	-7	7	-0.2	0.2
38	V. ALENTEJO	V.nave	2.89	3.05	-5	5	-0.2	0.2
39	V. BISPO	Vt-Vch.	1.93	1.78	8	8	0.1	0.1
40	V. N. AZEITÃO	V.nave	1.75	2.31	-25	25	-0.6	0.6
41	VOUZELA	V.nave	1.85	1.45	28	28	0.4	0.4
				AVG		16		0.49

APPENDIX M

RELATIONSHIPS BETWEEN RASTI AND ACOUSTICAL MEASURES INCLUDING U80

The Table M.1 presents the results for the squared correlation coefficients for the relations between RASTI and C80, U80, RT or EDT as a comparison between Bradley's work using 5 or 10 rooms and this study presented here. It must be clear that Bradley did not use the RASTI but Speech Intelligibility Scores using a Fairbanks rhyme test. Therefore the smaller R^2 that he found are reasonable due to the nature of his studies.

TABLE M.1 - RASTI vs. acoustical measures with third-order polynomials fitted to the data ($y = a + b.x + c.x^2 + d.x^3$).

ACOUSTICAL MEASURE	R^2 (Carvalho 1994)		R^2 (Bradley 1986A,B)	
	All Data	No Direct Field	All Data	S/N ≥ 10 dB
C80 125 Hz	**0.525**	0.512	0.030	n/a
C80 250 Hz	**0.529**	0.535	0.108	n/a
C80 500 Hz	**0.690**	0.652	0.195	0.250
C80 1 kHz	**0.680**	0.665	0.235	**0.352**
C80 2 kHz	**0.739**	0.684	0.339	n/a
C80 4 kHz	**0.685**	0.577	0.329	n/a
C80 8 kHz	**n/a**	n/a	0.275	n/a
U80 500 Hz	**0.693**	n/a	**0.771** / 0.682 (B)	0.321 / -
U80 2 kHz	**0.731**	n/a	**0.844** / 0.697 (B)	0.466 / -
RT 125 Hz	0.369	**0.632**	0.056	n/a
RT 250 Hz	0.394	**0.676**	0.099	n/a
RT 500 Hz	0.440	**0.737**	0.336	0.161
RT 1 kHz	0.438	**0.742**	0.371	0.288
RT 2 kHz	0.464	**0.758**	**0.412**	n/a
RT 4 kHz	0.478	**0.759**	0.326	n/a
RT 8 kHz	n/a	**n/a**	0.367	n/a
EDT 125 Hz	0.410	**0.629**	0.072	n/a
EDT 250 Hz	0.456	**0.695**	0.138	n/a
EDT 500 Hz	0.506	**0.779**	0.352	0.034
EDT 1 kHz	0.497	**0.771**	0.345	0.228
EDT 2 kHz	0.519	**0.776**	**0.389**	n/a
EDT 4 kHz	0.532	**0.766**	0.360	n/a
EDT 8 kHz	n/a	**n/a**	0.285	n/a

n/a - not available

	Carvalho (Churches)	Bradley A (Rooms)	Bradley B (Classrooms)
Number of rooms	41	5	10
Volume (m^3)	300 - 18000	400 - 20000	250 - 530
RT @ 1 kHz (s)	1.1 - 8.0	0.8 - 3.8	0.4 - 1.2
Number of points	145	≈ 160	160

APPENDIX N
COHERENCE VALUES MEASURED IN ALL CHURCHES

TABLE N.1 - Coherence data by 1/3 octave frequency bands.

	CHURCH	20	25	32	40	50	63	80	100	125	160	200	250	315	400	500
1	ALMANSIL	0.75	0.90	1	1	1	1	0.91	0.96	0.95	0.90	0.91	0.87	0.59	0.31	0.16
2	ARMAMAR	0.99	1	1	1	1	1	1	0.99	0.92	0.94	0.99	0.98	0.73	0.67	0.46
3	ESTRELA	0.93	0.99	1	1	1	1	0.99	0.99	0.98	0.99	0.94	0.86	0.77	0.73	0.45
4	BRAVAES	0.91	0.87	1	1	1	1	1	0.99	0.98	0.97	0.94	0.94	0.70	0.53	0.32
5	BUSTELO	0.91	0.99	0.96	1	1	1	1	0.99	1	0.99	0.97	0.97	0.68	0.66	0.37
6	CAB.SANTA	0.90	0.68	0.99	1	0.99	1	1	1	0.92	0.79	0.91	0.61	0.49	0.44	0.18
7	CAMINHA	1	1	1	1	1	1	1	0.96	1	0.90	1	1	0.88	0.53	0.37
8	CED.new	1	0.82	0.99	1	1	1	1	1	0.98	0.99	0.97	0.89	0.80	0.54	0.62
10	CETE	0.99	1	0.97	1	1	1	0.97	0.97	0.99	0.97	0.89	0.90	0.56	0.58	0.25
11	CLERIGOS	1	1	1	1	1	1	0.97	0.99	0.99	0.88	0.96	0.89	0.59	0.48	0.20
12	GOLEGA	1	1	1	1	1	1	1	1	1	0.93	0.94	0.94	0.85	0.66	0.37
13	LAPA	1	1	1	1	1	1	0.99	1	0.98	0.96	0.99	0.90	0.54	0.35	0.20
14	LECA	1	0.98	0.98	1	1	1	0.99	0.96	1	0.97	0.96	0.71	0.82	0.43	0.21
15	LOUROSA	0.92	0.55	0.92	1	1	1	1	1	1	0.99	0.98	0.91	0.85	0.87	0.61
16	MERTOLA	0.85	0.74	0.99	1	1	0.99	1	1	0.92	0.97	0.87	0.76	0.70	0.67	0.52
17	MISERIC	1	1	1	1	1	1	1	0.93	1	1	0.98	0.98	0.95	0.61	0.08
18	MOURA	1	1	1	1	1	0.99	0.93	0.96	0.91	0.94	0.90	0.77	0.68	0.35	0.28
19	BOAVISTA	1	1	1	1	1	1	1	0.95	0.98	0.86	0.76	0.63	0.61	0.85	0.52
20	P.SOUSA	0.99	0.99	1	1	1	1	1	1	0.94	0.99	0.97	0.74	0.64	0.38	0.21
21	S.SACR.	0.85	0.93	0.94	0.90	1	1	1	0.99	1	0.98	0.92	0.95	0.88	0.51	0.26
22	S.CLARA	0.99	1	1	1	1	1	1	0.99	1	1	0.97	0.79	0.76	0.42	0.25
23	CASTRIS	0.79	0.97	0.99	1	0.98	0.99	1	0.99	0.97	0.83	0.75	0.71	0.63	0.64	0.17
24	S.FRAN.ev	1	1	1	1	1	1	1	1	0.93	0.95	0.87	0.63	0.75	0.56	0.39
25	S.FRAN.po	1	1	1	1	1	1	1	1	1	1	1	1	1	0.80	0.55
26	S.FRUTU.	1	0.91	0.99	1	1	1	1	1	1	1	0.92	0.83	0.91	0.88	0.86
27	S.GENS	0.70	0.48	0.77	1	1	1	0.99	1	0.96	0.98	0.88	0.88	0.78	0.68	0.25
28	FERREIRA	0.69	1	1	1	1	0.99	0.87	0.99	0.98	0.95	0.96	0.87	0.44	0.20	0.12
29	RATES	0.79	1	1	1	1	1	1	1	0.98	0.98	0.91	0.89	0.80	0.59	0.32
30	RORIZ	1	1	0.96	1	1	1	1	0.97	0.94	0.99	0.92	0.82	0.93	0.55	0.29
31	S.ROQUE	0.99	1	1	1	1	1	1	1	1	1	0.94	0.97	0.91	0.71	0.49
32	LAMEGO	1	1	1	1	1	1	1	1	1	0.96	0.99	0.97	0.78	0.72	0.43
33	SEporto	1	1	1	1	1	1	1	1	1	0.99	0.97	0.91	0.68	0.47	0.16
34	SILVES	0.77	1	0.8	1	0.99	1	1	0.98	0.99	0.96	0.85	0.68	0.69	0.56	0.24
35	SEROA	0.65	0.73	1	1	1	1	0.98	0.99	0.92	0.88	0.82	0.70	0.75	0.75	0.52
37	TIBAES	0.99	0.93	1	1	1	1	0.99	1	1	1	0.98	0.88	0.73	0.63	0.47
38	V.ALENT.	0.86	1	1	1	1	0.97	1	0.9	0.96	0.98	0.92	0.81	0.61	0.32	0.21
39	V.BISPO	1	1	1	1	1	0.94	1	0.91	0.95	0.97	0.91	0.87	0.68	0.58	0.35
40	AZEITAO	1	1	0.99	1	1	0.99	1	1	1	0.98	0.92	0.87	0.78	0.62	0.39
41	VOUZELA	0.80	0.65	1	1	1	1	1	1	0.95	1	0.91	0.95	0.75	0.50	0.43
	Average	**0.92**	**0.93**	**0.98**	**1**	**1**	**1**	**0.99**	**0.98**	**0.97**	**0.96**	**0.93**	**0.85**	**0.73**	**0.57**	**0.35**

	CHURCH	630	800	1k	1250	1600	2k	2500	3150	4k	5k	6300	8k	10k		AVG
1	ALMANSIL	0.19	0.24	0.17	0.14	0.19	0.24	0.40	0.21	0.22	0.27	0.15	0.21	0.21		0.54
2	ARMAMAR	0.20	0.35	0.27	0.28	0.28	0.26	0.21	0.17	0.11	0.11	0.08	0.22	0.12		0.58
3	ESTRELA	0.26	0.34	0.34	0.31	0.57	0.60	0.34	0.47	0.33	0.10	0.26	0.08	0.49		0.65
4	BRAVAES	0.17	0.27	0.16	0.21	0.35	0.25	0.33	0.30	0.14	0.08	0.10	0.13	0.25		0.57
5	BUSTELO	0.22	0.15	0.30	0.43	0.18	0.22	0.21	0.10	0.13	0.09	0.10	0.18	0.14		0.57
6	CAB.SANTA	0.52	0.36	0.29	0.51	0.26	0.29	0.27	0.30	0.09	0.15	0.07	0.15	0.25		0.55
7	CAMINHA	0.48	0.21	0.52	0.38	0.28	0.34	0.45	0.46	0.22	0.03	0.14	0.08	0.23		0.62
8	CED.new	0.60	0.67	0.55	0.43	0.68	0.68	0.76	0.36	0.42	0.52	0.36	0.26	0.46		0.73
10	CETE	0.42	0.26	0.31	0.34	0.15	0.20	0.31	0.22	0.19	0.23	0.15	0.16	0.18		0.58
11	CLERIGOS	0.32	0.14	0.28	0.34	0.19	0.13	0.18	0.16	0.16	0.06	0.11	0.23	0.43		0.56
12	GOLEGA	0.23	0.27	0.27	0.39	0.22	0.24	0.12	0.09	0.04	0.08	0.06	0.09	0.18		0.57
13	LAPA	0.27	0.12	0.21	0.21	0.13	0.12	0.14	0.06	0.13	0.09	0.13	0.23	0.34		0.54
14	LECA	0.28	0.20	0.23	0.16	0.34	0.33	0.54	0.54	0.56	0.20	0.27	0.58	0.24		0.62
15	LOUROSA	0.65	0.42	0.52	0.34	0.27	0.38	0.08	0.09	0.18	0.19	0.12	0.13	0.08		0.61
16	MERTOLA	0.39	0.27	0.16	0.17	0.15	0.41	0.31	0.33	0.24	0.12	0.22	0.44	0.33		0.59
17	MISERIC	0.22	0.30	0.19	0.33	0.15	0.12	0.16	0.13	0.18	0.06	0.08	0.12	0.08		0.56
18	MOURA	0.29	0.16	0.14	0.23	0.25	0.19	0.13	0.13	0.12	0.06	0.10	0.21	0.17		0.53
19	BOAVISTA	0.58	0.63	0.44	0.45	0.47	0.32	0.42	0.58	0.10	0.15	0.30	0.55	0.76		0.68
20	P.SOUSA	0.25	0.23	0.37	0.19	0.27	0.15	0.20	0.14	0.21	0.17	0.09	0.12	0.09		0.55
21	S.SACR.	0.18	0.13	0.22	0.07	0.24	0.20	0.27	0.26	0.31	0.09	0.09	0.28	0.09		0.55
22	S.CLARA	0.14	0.29	0.51	0.43	0.21	0.19	0.47	0.27	0.11	0.16	0.21	0.14	0.19		0.59
23	CASTRIS	0.38	0.18	0.20	0.21	0.18	0.15	0.17	0.24	0.12	0.17	0.11	0.13	0.43		0.54
24	S.FRAN.ev	0.37	0.19	0.20	0.24	0.17	0.19	0.21	0.18	0.11	0.12	0.18	0.04	0.09		0.55
25	S.FRAN.po	0.30	0.50	0.48	0.22	0.21	0.47	0.26	0.62	0.93	0.35	0.43	0.41	0.68		0.72
26	S.FRUTU.	0.53	0.42	0.48	0.19	0.31	0.23	0.48	0.25	0.29	0.21	0.29	0.27	0.30		0.66
27	S.GENS	0.22	0.15	0.20	0.25	0.28	0.30	0.28	0.20	0.15	0.08	0.08	0.06	0.24		0.53
28	FERREIRA	0.24	0.23	0.22	0.20	0.14	0.17	0.24	0.19	0.11	0.08	0.18	0.11	0.19		0.51
29	RATES	0.25	0.25	0.32	0.34	0.16	0.13	0.27	0.29	0.13	0.10	0.12	0.04	0.15		0.56
30	RORIZ	0.17	0.28	0.19	0.47	0.32	0.29	0.20	0.21	0.22	0.16	0.20	0.09	0.44		0.59
31	S.ROQUE	0.55	0.31	0.22	0.23	0.31	0.26	0.20	0.39	0.11	0.05	0.25	0.14	0.32		0.62
32	LAMEGO	0.41	0.32	0.41	0.28	0.27	0.23	0.24	0.13	0.09	0.07	0.07	0.20	0.30		0.60
33	SEporto	0.12	0.13	0.12	0.27	0.45	0.27	0.21	0.36	0.36	0.12	0.16	0.37	0.46		0.59
34	SILVES	0.27	0.14	0.28	0.16	0.09	0.21	0.14	0.25	0.08	0.09	0.10	0.26	0.14		0.53
35	SEROA	0.24	0.43	0.45	0.47	0.31	0.21	0.49	0.35	0.52	0.16	0.43	0.57	0.37		0.63
37	TIBAES	0.41	0.52	0.30	0.28	0.41	0.39	0.25	0.15	0.26	0.22	0.12	0.17	0.64		0.63
38	V.ALENT.	0.27	0.18	0.15	0.21	0.16	0.26	0.16	0.13	0.25	0.32	0.21	0.84	0.67		0.58
39	V.BISPO	0.16	0.16	0.19	0.32	0.32	0.32	0.74	0.44	0.13	0.10	0.11	0.29	0.19		0.59
40	AZEITAO	0.22	0.24	0.25	0.12	0.19	0.35	0.25	0.22	0.11	0.13	0.09	0.06	0.17		0.57
41	VOUZELA	0.38	0.25	0.37	0.44	0.27	0.07	0.09	0.12	0.56	0.18	0.30	0.31	0.85		0.61
	Average	**0.32**	**0.28**	**0.29**	**0.29**	**0.27**	**0.27**	**0.29**	**0.26**	**0.22**	**0.15**	**0.17**	**0.23**	**0.31**		**0.59**

APPENDIX O
LIST OF CHURCHES WITH SUBJECTIVE QUALITY RATINGS

TABLE O.1 - List of 41 churches tested with subjective quality ratings.

	CHURCH	Subj. Qual.		CHURCH	Subj. Qual.
1	ALMANSIL	4	22	SANTA CLARA porto	4
2	ARMAMAR	2	23	S. B. CASTRIS évora	3
3	BAS. ESTRELA lisboa	4	24	S. FRANCISCO évora	3
4	BRAVÃES	4	25	S. FRANCISCO porto	5
5	BUSTELO	1	26	S. FRUTUOSO	4
6	CABEÇA SANTA	4	27	S. GENS boelhe	3
7	CAMINHA	4	28	S. P. FERREIRA	2
8	CEDOFEITA.new porto	5	29	S. P. RATES	4
9	CEDOFEITA.old porto	2	30	S. P. RORIZ	4
10	CETE	4	31	S. ROQUE lisboa	5
11	CLÉRIGOS porto	2	32	SÉ lamego	1
12	GOLEGÃ	2	33	SÉ porto	4
13	LAPA porto	4	34	SÉ silves	4
14	LEÇA DO BAILIO	5	35	SERÔA	2
15	LOUROSA	3	36	SERRA PILAR gaia	1
16	MÉRTOLA	4	37	TIBÃES	5
17	MISERICÓRDIA évora	4	38	VIANA DO ALENTEJO	4
18	MOURA	1	39	VILA DO BISPO	5
19	N. S. BOAVISTA porto	5	40	V. N. AZEITÃO	3
20	PAÇO SOUSA	3	41	VOUZELA	5
21	SANT. SACRAM. porto	4			

Subjective Quality:

1 *VERY BAD*
2 *BAD*
3 *NORMAL*
4 *GOOD*
5 *VERY GOOD*

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BIOGRAPHICAL SKETCH

The author was born in Porto, Portugal, in 1960. He finished high school at the Liceu Nacional in V. N. Gaia in 1977 and graduated from the University of Porto in civil engineering, majoring in building construction, in 1983 where he also obtained the degree of Master of Science in 1988. The writer taught several courses at the University of Porto, College of Engineering, between 1983 and 1991 and is on leave to pursue his Ph.D. degree. He was an acoustical consultant between 1987 and 1992. He is the director of the Acoustical Laboratory of the College of Engineering. He is a recipient of scholarships from the binational Fulbright Commission and JNICT/Portuguese Ministry of Planning during his studies in the United States of America. The author received the 1994 Robert Newman Award for excellence in architectural acoustics, the First Prize Award for Best Paper in the 1994 U. F. Graduate Student Forum and the 1994 *Progressive Architecture*/American Institute of Architects Research Award (in team). He also received, from 1986 to 1991, six European Community *TEMPUS* and *ERASMUS* grants. He is a member of several technical societies in the U.S.A. and Portugal and author of several papers and articles in diverse acoustical fields.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Earl Starnes, Chairman
Professor Emeritus of Architecture

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Gary W. Siebein, Cochairman
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Willis Bodine
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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December, 1994

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